View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by UNL | Libraries

University of Nebraska - Lincoln
DigitalCommons@University of Nebraska - Lincoln

Civil Engineering Faculty Publications | Civil Engineering

2018

Sustainable Waste-to-Energy Technologies: Bioelectrochemical Systems

Rami Ziara
University of Nebraska - Lincoln, rziara@hotmail.com

Bruce Dvorak
University of Nebraska - Lincoln, bdvorak1@unl.edu

Jeyamkondan Subbiah
University of Nebraska-Lincoln, jeyam.subbiah@unl.edu

Follow this and additional works at: http://digitalcommons.unl.edu/civilengfacpub


Part of the Biochemical and Biomolecular Engineering Commons, Environmental Engineering Commons, and the Other Civil and Environmental Engineering Commons

Ziara, Rami; Dvorak, Bruce; and Subbiah, Jeyamkondan, "Sustainable Waste-to-Energy Technologies: Bioelectrochemical Systems" (2018). *Civil Engineering Faculty Publications*. 136.
http://digitalcommons.unl.edu/civilengfacpub/136

This Article is brought to you for free and open access by the Civil Engineering at DigitalCommons@University of Nebraska - Lincoln. It has been accepted for inclusion in Civil Engineering Faculty Publications by an authorized administrator of DigitalCommons@University of Nebraska - Lincoln.

University of Nebraska Lincoln
digitalcommons.unl.edu

Published in *Sustainable Food Waste-to-Energy Systems,* ed. Thomas Trabold & Callie W. Babbitt (Academic Press, 2018), pp 111–140.
doi 10.1016/B978-0-12-811157-4.00007-3
Copyright © 2018 Elsevier Inc. Used by permission.

Sustainable Waste-to-Energy Technologies: Bioelectrochemical Systems

Rami M. M. Ziara,[1] Bruce I. Dvorak,[2] and Jeyamkondan Subbiah[3]

1 Department of Civil Engineering, University of Nebraska–Lincoln, Lincoln, NE, United States
2 Department of Civil Engineering and Department of Biological Systems Engineering, University of Nebraska–Lincoln, Lincoln, NE, United States
3 Department of Biological Systems Engineering and Department of Food Science and Technology, University of Nebraska–Lincoln, Lincoln, NE, United States

1 Introduction

Bioelectrochemical systems (BESs) are systems that use microorganisms to biochemically catalyze complex substrates into useful energy products, in which the catalytic reactions take place on electrodes. In other words, BESs are battery-like systems in which a biofilm grown on electrodes oxidizes substrates and generates energy. In wastewater treatment, a substrate refers to a contaminant that needs to be removed. For example, the major substrate removed from wastewater is organic matter which can be measured using different wastewater characteristics including chemical oxygen demand (COD) and biochemical oxygen demand (BOD). Wastewater characteristics could be represented as the total substrate concentration (e.g., Total BOD or Total COD) or concentration of the soluble substrates in the wastewater (e.g., soluble BOD or soluble COD). BESs are advantageous due to their ability to achieve a degree of substrate removal while generating

energy. Typically, the energy generated from BESs is either in the form of electricity or energy-rich gasses. Therefore it is a promising technology toward energy positive or energy neutral treatment systems.

Potter (1911) was the first to report that electric potential can be produced in a cell using microorganisms; however, this technology did not gain much attention until the beginning of the 21st century. Over the past two decades, significant effort has been exerted in order to understand and develop BESs (Aghababaie et al., 2015; Wang et al., 2015). Many reactor configurations, architectures, and materials have been evaluated in efforts to optimize the technology. Thus different BESs types have emerged including:

(i) microbial fuel cells (MFCs), which oxidize the substrate and generate electric power concurrently (Logan et al., 2006),

(ii) microbial electrolysis cells (MECs) or bioelectrochemically assisted microbial reactors (BEAMRs), for which an external power source is added to oxidize a substrate while generating useful by-products (Ditzig et al., 2007; Escapa et al., 2012),

(iii) enzymatic biofuel cells, which use specific enzymes to oxidize the substrate and the enzymes are responsible for the transfer of electrons to the electrodes (Leech et al., 2012),

(iv) microbial electrosynthesis cells which are used to synthesize organic chemicals from the substrate (Nevin et al., 2010), and

(v) microbial desalination cells which can remove salinity from the substrate (Cao et al., 2009).

Logan et al. (2015) provided a comprehensive summary of additional secondary type MFCs and their relative performance. Most of BESs types were evaluated using nonfood source substrates. However, the studies that evaluated food waste focused mainly on MFCs and MECs, thus this chapter focuses on these two types of BESs.

The food industry produces a large amount of waste and wastewater. In the United States, fruits, vegetables, dairy, and grain products are the most common wasted foods, while in the UK, fruits, vegetables, bakery, and dairy are among the top wasted foods (Kosseva, 2013). Carbohydrates, proteins, lipids, and organic fibers constitute the majority of the waste mass, which makes food waste highly biodegradable and energy rich. Food production and processing are associated with the use of resources including water and energy. In addition, a large amount of waste

and wastewater loads are generated during the production of food and must be treated before discharge. The constituents of the wastewater differ from industry to industry but generally, organic matter is the largest constituent of food industry wastewater. Summaries of waste and wastewater characteristics produced from food industries are provided through this chapter, as well as in Chapter 2 ("Waste resources in the food supply chain," by Thomas A. Trabold, Shwe Sin Win and Swati Hegde). More detailed reviews of the wastes and wastewater produced from the food industry can also be found in earlier publications (e.g., ElMekawy et al., 2015; Kosseva, 2013).

2 Theoretical Background and Performance Indicators

One of the advantages of the bioelectrochemical systems is that energy can be produced simultaneously while treating the wastewater through substrate degradation. In BESs, electrochemical reactions are carried out by a specific group of bacteria, exoelectrogens, which can transfer electrons outside the microbial cell (Kiely et al., 2011b; Liu et al., 2014; Logan, 2009; Sun et al., 2014). The fundamental principle behind BESs is redox potential. Gibbs free energy (ΔG^0) is the energy available in a chemical reaction to do useful work. Exergonic reactions produce energy ($\Delta G^o < 0$), while endergonic reactions require energy to occur ($\Delta G^o > 0$). Furthermore, Gibbs free energy can be converted into the electric potential using Nernst's law ($E^o = -\Delta G^\circ/nF$), where n is the number of electrons transferred in a chemical reactions and F is Faraday's constant (96,485 C/mol). Moreover, the electromotive force is the electrical potential available between an oxidizing reaction and a reduction reaction ($E^o_{emf} = E^o_{red} - E^o_{oxi}$), where E^o_{red} and E^o_{oxi} are the electric potential for the reduction reaction and oxidation reaction, respectively.

2.1 Microbial Fuel Cells (MFCs)

Microbial fuel cells are a type of bioelectrochemical systems that oxidize substrates and generate electric current (i.e., $E^o_{emf} > 0$) (Logan et al., 2006). A typical MFC contains two electrodes, anode and cathode, connected externally to a load or resistor and separated by a membrane. The oxidation of the substrate occurs at the anode and generates electrons (e^-) and protons (H^+). The electrons are transferred from the microorganisms into the electrode. Three means are reported in the literature by

which electrons are shuttled from the microorganisms to the electrode; direct electron transfer, transfer through nanowire structures and through a mediator (Philips et al., 2016; Rabaey and Verstraete, 2005). The protons travel from the anode chamber to the cathode chamber through the liquid and ion exchange membrane, if applicable. The electrons and protons react with the terminal electron acceptor on the cathode. The terminal electron acceptor can theoretically be any chemical that has a redox potential less than that of the electron donor, for example, oxygen or nitrate. The transport of electrons through the external wire generates the electric current. The maximum voltage that can be produced by an MFC is limited by the thermodynamic relationships between the electron donor and the electron acceptor (E^{o}_{emf}), as well as losses inside the cell. Electron losses are due to oxidation activation losses ($\eta_{oxi,\ act}$) and reduction activation losses ($\eta_{red,\ act}$); internal resistance (IR) of the cell due to losses in electrodes, electrolytes, membrane, and connections; and losses associated with mass transport and diffusion (η_{mt}) (Logan et al., 2006; Rabaey and Verstraete, 2005). The cell electrical potential is therefore

$$E_{cell} = E_{emf} - \eta_{oxi,\ act} - \eta_{red,\ act} - IR - \eta_{mt}.$$

A typical microbial fuel cell design that contains two electrodes connected by a resistor (load) and separated by a membrane is illustrated in **Fig. 1.** The oxidation of substrate or wastewater is achieved by the biofilm that grows on the anode. Electrons produced from the oxidation of organic matter travel from the anode chamber to the cathode chamber where they are used in a reduction reaction at the cathode. In the shown case, the terminal electron acceptor is oxygen; however, other electron acceptors can be utilized including nitrate and sulfate. Several MFC architectures have been developed; the most commonly used are two-chamber MFC (TC-MFC) and single-chamber MFC (SC-MFC). **Fig. 1** shows the architecture of a two-chamber microbial fuel cell, which has an anode and a cathode chamber separated by an ion exchange membrane. Single-chamber microbial fuel cells are MFCs that have a single chamber in which both electrodes are placed (Cheng et al., 2011). The use of ion exchange membrane in a SC-MFC is optional and when used it could be placed directly on the electrode. Tubular MFCs have a tube- or pipe-like architecture (Rabaey et al., 2005), while a three-chamber MFC has three chambers separated by ion exchange membranes (Zhang et al., 2013). Several sources are available for further reading on MFC architectures and materials used (Bajracharya et al., 2016; Du et al., 2007; Dumitru and Scott, 2016; Logan, 2008; Scott, 2016; Silver et al., 2014).

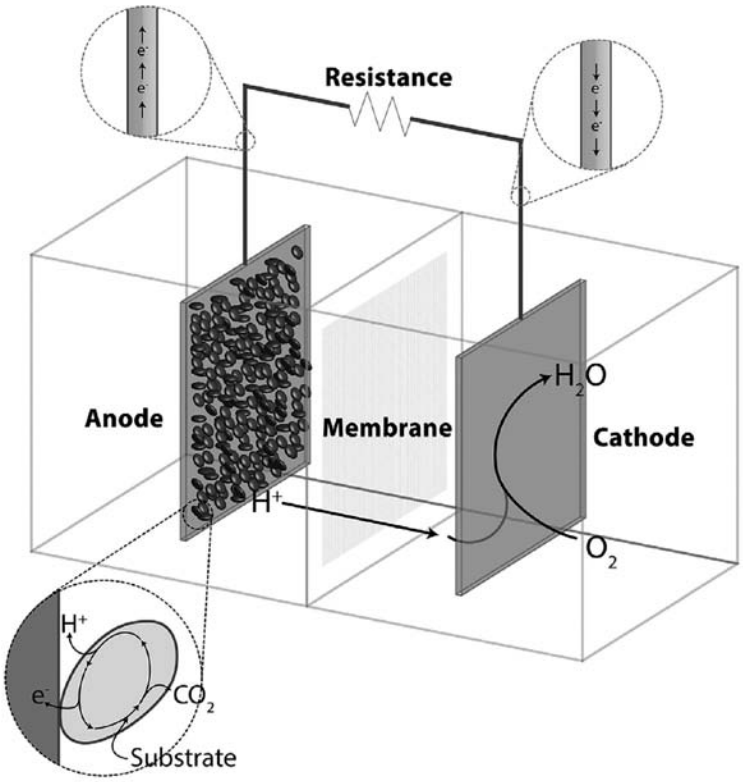

Fig. 1. A typical design of two-chamber microbial fuel cell (TC-MFC) which contains the anode and cathode chambers separated by ion exchange membrane.

The performance of an MFC can be assessed based on several indicators, including power density, current density, coulombic efficiency (*CE*), and substrate reduction (e.g., *ΔCOD*). Power is the product of current and voltage, with current being an indication of electrons flow. Power and current densities are usually normalized by the anodic surface area (A_{an}) since the biofilm that oxidizes the substrate grows on the anode. Furthermore, power and current densities are sometimes normalized by the working volume of the cell. The current produced from a microbial fuel cell is usually small (<1A/m^2) since it is related to biochemical reactions that are limited by substrate utilization rate and electron production. Coulombic efficiency (*CE*) is a parameter that indicates the fraction of electrons recovered as current, compared to that originally present in the organic matter. Therefore *CE* is an important indicator in mixed culture MFCs, where multiple microbial species compete for the substrate and it also can reflect electron loss in the cell. For more information on measurement and calculation methods, the reader is referred to Logan et al. (2006).

2.2 Microbial Electrolysis Cells (MECs)

Microbial electrolysis cells (MECs) are a type of bioelectrochemical systems that use an external power source to catalyze the substrate into by-products. This type of BES has been given many names, including BEAMR, biocatalyzed electrolysis cell (BEC), and microbial electrolysis cell (MEC) (Ditzig et al., 2007; Escapa et al., 2012). The latter, MEC, is the most commonly used. The external power is needed to force thermodynamically unfavorable reactions ($\Delta G^o > 0$) to occur. Products ranging from methane (CH_4), to hydrogen gas (H_2), to hydrogen peroxide (H_2O_2) can be produced using MECs, depending on the redox reactions involved (Rozendal et al., 2009; Wagner et al., 2009).

Several MEC architectures have been evaluated, but generally most MFC architectures and materials are applicable for MECs, including TC-MEC, SC-MEC, and tubular MEC; the difference is that the cathode also operates under anaerobic condition. A typical two-chamber MEC is illustrated in **Fig. 2.** In MECs, electrons and protons are produced on the anode. The electrons travel through the electrode and the protons travel through the liquid to the cathode. The redox potential of the anodic and cathodic reactions is not enough to move these reactions forward, therefore an external power source is needed. Research studies have established that using a biocathode in MECs is more efficient than using an abiotic, microorganism-free, cathode (Rozendal et al., 2008; Wang et al., 2014; Xu et al., 2014). The theoretical voltage required to achieve a specific reaction can be calculated using (E^o_{emf}), which will be negative in the case of MEC. Like MFCs, voltage losses occur within the cell, therefore the voltage needed to be added is usually slightly higher than the theoretical voltage.

The performance of an MEC can be assessed using multiple indicators, including *CE*, hydrogen yield (Y_{H_2}), cathodic hydrogen recovery (r_{cat}), overall hydrogen recovery (r_{H_2}), volumetric density, and hydrogen production rate (Call and Logan, 2008; Logan, 2008). Hydrogen yield is the mass fraction of the hydrogen produced to the substrate removed. The cathodic hydrogen recovery (r_{cat}) represents the fraction of hydrogen recovered to the estimated hydrogen produced based on measured current. The overall hydrogen recovery (r_{H_2}) is the efficiency of hydrogen production based on the total hydrogen moles recovered versus the theoretical possible production. The energy efficiency (η_W) is the efficiency based on the applied voltage. The volumetric hydrogen production rate (Q) represents how much

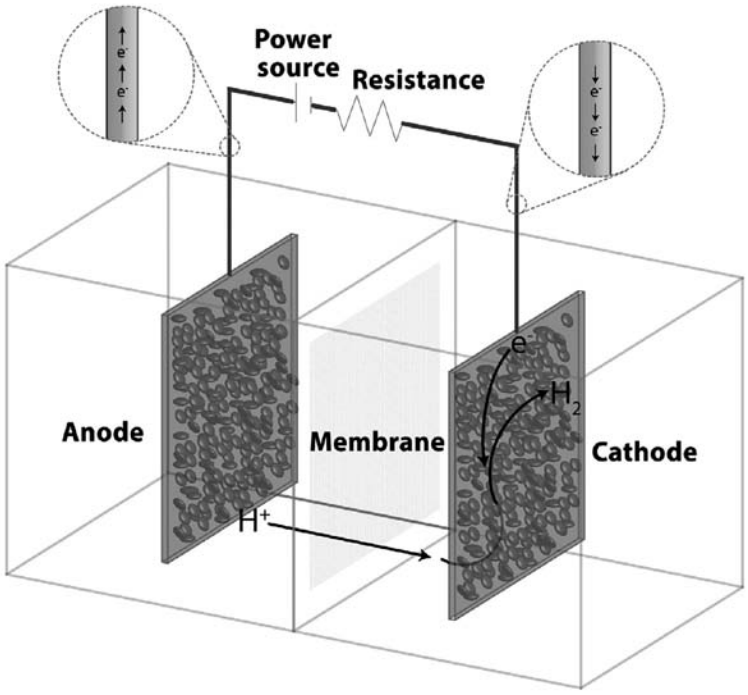

Fig. 2. A typical design of a two-chamber microbial electrolysis cell (TC-MEC) which has two chambers separated by ion exchange membrane.

hydrogen is produced per unit volume of reactor per unit time. For more information on measurement and calculation methods, the reader is referred to Call and Logan (2008) and Logan (2008).

3 Energy Recovery from Food Industry Wastes Using BESs

3.1 Microbial Fuel Cells

MFCs are bioelectrochemical systems that can achieve substrate removal and generate power simultaneously. Several architectures for MFCs exist; however, only a few have been evaluated using food industry wastes. Most of the food industry wastewater was evaluated using two-chamber MFCs and single-chamber MFCs at laboratory scales. The performance of MFCs using food wastes can be categorized according to the source of the waste as follows.

3.1.1 Brewery and Winery Wastewater

Brewery wastewater has high concentrations of carbohydrates and sugars which have high energy content and can be easily biodegraded (Wang et al., 2016). Due to wastewater generation patterns and variability among brewery and winery wastewater sources, traditionally biological wastewater treatment technologies are employed, including sequencing batch reactors (SBRs) and up-flow sludge blankets (USABs) systems (Simate et al., 2011). Aerobic and anaerobic biological treatment processes can achieve 70%–98% COD removal; however, the energy requirement for these processes is high (Feng et al., 2008). Therefore the use of MFC systems for brewery wastewater has been investigated extensively and has even been commercialized (Pandey et al., 2016).

Previous studies of MFCs to treat brewery and alcohol-based wastewaters have investigated parameters including substrate concentration, reactor configuration, electrode materials, and mixing with other substrates in batch and continuous operations modes. Table 7.1 provides a summary of the performance, reactor design, and materials used in 19 studies that evaluated the performance of MFCs using brewery and alcohol-based wastewaters. Most of the studies investigated cells with small working volume (<500 mL). Two studies investigated 4L and 10L MFC.

The highest power density using brewery wastewater was achieved using winery wastewater (6850 mg COD/L) in a tubular MFC with working volume of 170 mL (Penteado et al., 2016a). Their cell achieved a maximum power density of 890 mW/m^2, 10% COD removal, and maximum coulombic efficiency of 42.2%. Different solids retention times (SRT) were evaluated and Penteado et al. (2016a) concluded that SRT does not have a significant impact on biological treatment but has an effect on coulombic efficiency and power density. Feng et al. (2008) achieved the highest reported COD reduction of diluted brewery wastewater using single-chamber MFC (up to 98%), however lower power density (29–205 mW/m^2) was achieved; this study demonstrates that treating brewery wastewater with MFCs has the potential to be competitive with traditional energy-intensive biological processes.

A 4-L single-chamber MFC was investigated using diluted brewery wastewater (3707 mg COD/L); it produced 304 mW/m^2 and achieved >75% COD reduction (Wang et al., 2016). Despite this large COD removal, the coulombic efficiency was low which indicates that the organic matter might have been oxidized by fermentative and methanogenic microorganisms instead of exoelectrogens.

Zhuang et al. (2012) scaled up an MFC to 10 L and operated it for 180 days continuously. A maximum power density of 4.1 W/m^3 was produced at 30 days of operation and power density dropped by 60% by the end of the experiment. The long-term COD removal rate was more stable than the power generation; the cell maintained COD removal larger than 85% throughout the experiment. The reported coulombic efficiency was low and >35% of the COD removed was estimated to be associated with non-exoelectrogenic microorganisms. However, high ammonia removal was concurrently achieved, which demonstrated the system's ability to treat multiple substrates. Zhuang et al.'s (2012) study demonstrates the MFC's general limitation: high electron loses in scaled-up systems.

Generally, two-chamber MFCs produced less current and achieved lower coulombic efficiency than single-chamber MFCs due to internal potential losses (Çetinkaya et al., 2015; Pisutpaisal and Sirisukpoca, 2012). Previous studies have shown that high COD and ammonia removal can be achieved using MFCs to treat brewery wastewater. However, proper methanogenic control should be employed to ensure that COD reduction is achieved by exoelectrogenic microorganisms and maximum coulombic efficiency is achieved. It is important to note that MFCs cannot achieve the required treatment for wastewater discharge, therefore they must be combined with a secondary process to further remove contaminants. The performance of MFC is similar to the performance of anaerobic technologies treating the same wastewater, and therefore MFC can compete with conventional anaerobic technologies.

3.1.2 Cafeteria and Canteen Wastes

Most cafeteria wastes are food leftovers that contain rice, bread, vegetables, oil, and meat products (Goud et al., 2011). Cafeteria and canteen wastes and wastewater were mostly investigated in a single-chamber or solid-phase MFC. Previous studies of MFCs to treat cafeteria and canteen wastes have investigated different parameters, including substrate concentration, reactor configuration, electrode materials, and pretreatment options in mostly batch operation modes. **Table 2** provides a summary of the performance, reactor design, and materials used in 10 studies that evaluated the performance of MFCs using cafeteria and canteen wastes. Most of the studies investigated single- and two-chamber MFCs with small working volume (<500 mL).

Choi and Ahn (2015) fermented cafeteria waste and used the high strength leachate in a small single-chamber MFC. The cell power density

was 1540 mW/m^2, the maximum reported from cafeteria waste. The cell also achieved high COD removal (85.1%) and high coulombic efficiency (88.8%). Sangeetha and Muthukumar (2011) investigated using canteen wastewater (COD; 7760 mg/L) and the cell achieved the highest COD removal reported for cafeteria and canteen waste, nearly 99%. However, the cell produced a maximum power density of only about 124 mW/m^2.

The studies reported for canteen and cafeteria-based waste show that MFCs can achieve high COD removal and high coulombic efficiencies. These studies also demonstrate that employing anaerobic fermentation as a waste pretreatment strategy for using high strength wastes is feasible. Similarly, higher power densities were reported by researchers who integrated fermentation of food wastes with MFC (Li et al., 2013; Rikame et al., 2012).

3.1.3 Dairy Industry and Cheese Whey

The dairy industry produces a large quantity of high-strength wastewater, with reported ranges of COD from 0.38 to 72.5 g/L, BOD from 0.19 to 68.6 mg/L, and up to 1462mg TKN/L (Britz and van Schalkwyk, 2005). Several sources provide more specific dairy industry wastewater characterization (Britz and van Schalkwyk, 2005; Danalewich et al., 1998). Anaerobic biological treatment systems are usually used for the treatment of dairy industry wastewater, which includes UASB, up-flow anaerobic filters, and anaerobic suspended growth reactors, which can achieve 70%–99% COD reduction (Britz and van Schalkwyk, 2005; Demirel et al., 2005; Mohan et al., 2010b). Dairy industry wastewater has high concentrations of lipid, protein, and lactose content, and some of this may be emitted in the wastewater. These wastewater characteristics have encouraged researchers to investigate the performance of MFCs as a treatment and energy recovery technology. **Table 3** provides a summary of the performance, reactor design, and materials used in 16 studies that evaluated the performance of MFCs using dairy industry waste and wastewater. Most of the studies investigated single- and two-chamber MFCs with working volume ranging between 28 and 2000 mL.

Dairy wastewater (3620mg COD/L) was investigated by Mansoorian et al. (2016) in a two-chamber MFC and produced a maximum power density of 621 mW/m^2, which is the highest power density reported among studies listed in Table 3. The Mansoorian et al. (2016) study also reported >90% COD reduction and coulombic efficiency higher than 37%. Mohan et al. (2010b) investigated using diluted dairy wastewater in a single-chamber

MFC under different organic loadings. The cell achieved the maximum COD removal reported for dairy industry wastewater (95%), however the cell achieved low coulombic efficiency and low power density. Mohan et al. (2010b) study also documented that high protein, turbidity, and carbohydrates removal can be achieved using MFC for the treatment of dairy wastewater. Kiely et al. (2011a) investigated using dairy manure (4300 mg COD/L) in a single-chamber small MFC operated in batch mode. The cell achieved a maximum power density of 189 mW/m^2, 70% COD reduction, and 12% coulombic efficiency. Zhang et al. (2015) investigated the performance of three-chamber MFC, two cathodes and one anode, in electricity production from dairy manure. The cell produced up to 14,000mW/m^3 and reduced the COD by 4434–8302 mg/L.

Even though low power densities were achieved by MFCs using dairy wastewater, the COD removal indicates that if MFCs are better understood and optimized, they could be a viable alternative for current dairy wastewater treatment technologies.

3.1.4 Fruits, Vegetables, and Food Wastes

Fruit and vegetables constitute 20%–50% of household wastes. The percent of the fruit and vegetable in household waste is proportional to the proportion of vegetable and fruits in a country's diet (Bouallagui et al., 2003; Pekan et al., 2006). Further research concluded that the composition of fruit and vegetable wastes is related to the harvest period, demand for a product, handling requirements, and shelf life of the fruits and vegetables (Angulo et al., 2012; Kosseva, 2013). Thassitou and Arvanitoyannis (2001) collected the wastewater characteristics of fruit and vegetable processing industries including apples, carrots, cherries, corn, grapefruit, green peas, and tomatoes. The reported range of COD was 1.5–18.7 g/L, BOD was 0.8–9.6 g/L, and suspended solids was 0.21–4.12 g/L. **Table 4** provides a summary of the performance, reactor design, and materials used in studies that evaluated the performance of MFCs using a variety of fruit, vegetable, and food wastes. Most of the studies investigated single- and two-chamber MFCs with working volume ranging between 25 and 1000mL.

The highest power density reported for fruit and vegetable processing wastewater was achieved in a single-chamber MFC (Oh and Logan, 2005). However, the maximum power density achieved by a two-chamber MFC using the same wastewater dropped significantly, even though similar COD removal was achieved in both cells, as listed in Table 4. This demonstrates that

two-chamber MFC has electron losses. Recently, Tian et al. (2017) evaluated the performance of small single-chamber MFC using potato pulp waste. The waste was diluted and the COD ranged between 2000 and 25,000 mg/L. The cell produced moderate power level that ranged between 20,400 and 32,100mW/m^3 and achieved up to 68% COD reduction and up to 56% coulombic efficiency. However, Kiely et al. (2011a) was able to achieve higher COD removal using potato processing wastewater. Shrestha et al. (2016) investigated using tomato processing waste in two-chamber MFC. The tomato seeds and skin produced a maximum power density of 132mW/m^2 while the tomato cull produced a maximum power density of 256mW/m^2. Composited vegetable waste was investigated in a single-chamber, 430-mL MFC (Mohan et al., 2010a). The COD loading was varied from 0.70 to 2.08 kg/m^3/d and the cell achieved up to 63% COD reduction. The cell produced power density up to 216 mW/m^2.

The reported literature shows that 60%–85% COD removal can be achieved using MFC systems to treat fruit, vegetable, and food wastewater. In addition, lower power densities are generally achieved using this type of wastewater than that achieved by other wastewater. Further studies are needed particularly to evaluate the performance of scaled-up MFCs and how wastewater pretreatment, such as fermentation, may enhance the performance of MFC treating this wastewater. In addition, the economic feasibility of integrating MFC in vegetable and fruit waste treatment scheme must be evaluated since very high reduction COD cannot be achieved using MFC alone for this type of waste.

3.1.5 Animal Processing and Meat Industry

The global meat production was 280 million tones in 2008, with the production predicted to double by 2050 (Kosseva, 2013). To supply this global meat demand, livestock operations are intensified and thus produce large quantities of wastes and greenhouse gas emissions, which contribute to climate change (Caro et al., 2017; de Vries and de Boer, 2010; Naylor et al., 2005; Stehfest et al., 2013). The approximate edible mass portions of cows, sheep or goats, pigs, chicken, and turkey are 50%–54%, 52%, 60%–62%, 68%–72%, and 78%, respectively (Kosseva, 2013). Furthermore, meat processing in slaughterhouses and packing plants requires a large amount of water, for washing and cleaning, which is then discharged as wastewater. For example, the water used in a mid-size beef packing plant is approximately 3000L/1000 kg live weight slaughtered (Ziara et al., 2016).

Meat processing wastewater is generally of high strength. Cattle

slaughterhouse wastewaters have COD range of 3–12.9 g/L range, BOD of 0.9–7.24 g/L, average suspended solids (SS) of 3.6 g/L, average total nitrogen (TN) of 378 mg/L, and average total phosphorous (TP) around 79 mg/L (Banks and Wang, 2005; Kosseva, 2013). For hog slaughterhouses, the wastewater COD is about 3g/L, BOD is in the 1.95–2.22 g/L range, average SS of 3.7 g/L, TN range of 14.3–253 mg/L, and TP range of 5.2–154 mg/L (Banks and Wang, 2005; Kosseva, 2013). The constituents of animal and meat-based industry are complex and not easily biodegradable, therefore anaerobic technologies are used the most in the industry followed by secondary treatment for additional organics and nutrient removal (Banks and Wang, 2005). **Table 5** provides a summary of the performance, reactor design, and materials used in 25 studies that evaluated the performance of MFCs using animal processing and meat industry waste and wastewaters. Most of the studies using this type of waste investigated cells with larger working volume (up to 2500mL) than other wastewater sources discussed previously. Most of the studies focused on investigating two-chamber MFCs in both batch and continuous modes.

Using goat rumen fluid and hay in four two-chamber MFCs connected in series, Meignanalakshmi and Kumar (2016) reported the highest power density range of 34,390–42,110 mW/m^2 achieved using the waste type discussed in this section. However, further MFC performance indicators were not reported. Ismail and Mohammed (2016) reported the highest COD removal (99%) achieved using slaughterhouse wastewater in a tubular MFC operated in continuous mode. The highest coulombic efficiency of 47% was reported by Ichihashi and Hirooka (2012), who used swine slurry in a single-chamber MFC.

Swine waste produces significant greenhouse gas emissions during waste management operations, and therefore it has attracted special attention and is one of the most widely investigated wastes using BESs (Caro et al., 2017). Ma et al. (2016) achieved the highest power density (880–1056 mW/m^2) of the swine waste studies listed in **Table 5** using swine farm wastewater in a two-chamber MFC. The anode was carbon fiber brush and the cathode was carbon cloth with Pt catalyst; other information was not reported. In a study aimed at evaluating the microbial dynamics in a continuous MFC, it was reported that that up to 5623 mW/m^3 was produced using swine slurry (Sotres et al., 2016). No other data was reported in that study regarding COD removal or coulombic efficiency. Zheng and Nirmalakhandan (2010) investigated the performance of two-chamber 1.85-L MFC using manure wash wastewater. The cell produced 216 mW/m^2 (2000 mW/m^3) and maximum coulombic efficiency of 5.2%.

Slaughterhouse and meat packing wastewater were also investigated using MFCs. Heilmann and Logan (2006) used diluted meat packing wastewater in a single-chamber MFC. The cell achieved >86% COD reduction, a maximum power density of 139 mW/m^2, and a maximum coulombic efficiency of 6%. The low coulombic efficiency indicates high internal resistance or that most of the COD reduction was achieved mainly by nonexoelectrogens.

Sulfur-based compounds can be present at higher concentrations in cattle and swine wastes. Hydrogen sulfide (H_2S) is the main sulfur-based emission from confined animal feedlot operations (CAFOs), which results from microbial degradation of sulfide (Rumsey and Aneja, 2014). Furthermore, sulfate-reducing bacteria such as *Desulfovibrio* and *Desulfotomaculum* use lactate as the main electron donor; lactic acid is one of the main organic acids used in slaughterhouses as an antimicrobial intervention (Algino et al., 2007; Ueki et al., 1986). Other bacteria such as *Desulfobacter postgatei, Desulfobulbus propionicus*, and *Desulfonema* can use acetate, proportionate and long-chain fatty acids as the main electron donor, which are the end products of anaerobic fermentation (Boone, 1982; Ueki et al., 1986, 1989, 1991). Three main sources of sulfur-based compounds have been identified: animal feed, degradation of animal proteins, and sulfate-based chemicals used for tanning hides (Abreu and Toffoli, 2009; Crawford, 2007; Miner, 1976; Sapkota et al., 2007; Sundar et al., 2002). Rabaey et al. (2006) and Zhao et al. (2009) showed that sulfur-based chemicals can be removed by MFCs. However, the performance of MFC in removing sulfur-based compounds from actual meat and animal-based wastewater has not been evaluated.

The studies reported in this section showed the potential of energy generation and treatment of animal waste and the meat processing wastewater. However, further research is needed to optimize the systems, evaluate pretreatment methods, and evaluate sulfur-based compound removal. Scaled-up systems still need to be developed and better methods for reduction of internal resistance and methanogenic control need to be researched.

3.1.6 Sugar-Based and Distillery Wastewater

Molasses wastewater is produced from sugar-based industry. Molasses wastewater is of high strength with COD ranging between 65,000 and 130,000 mg/L, low pH, and high concentrations of sugars and salts (Lee et al., 2016). The main by-product of distilleries is wastewater, with the

wastewater volume being approximately 10 times larger than the volume of ethanol produced (Kosseva, 2013). The wastewater produced from distilleries is of high strength with COD range between 18,000 and 122,000 mg/L, high solids content, and low pH. The wastewater characteristics from distilleries depend on many factors including the feedstock, size, and capacity of plants, and wastewater utilization and biodegradation. Traditionally, molasses and distillery wastewater is treated using anaerobic processes, but has also been an attractive source for microbial fuel cells, due to the simplicity of the organic content which is primarily sugars (Pant and Adholeya, 2007). Table 6 provides a summary of the performance, reactor design, and materials used in studies that evaluated the performance of MFCs using molasses, distillery, and other sugar-based wastewater.

Most of the studies investigated either single- or two-chamber MFCs with working volume ranging between 25 and 1000 mL operated in batch mode. The highest power density among reported studies ranging between 331 and 343 mW/m^2 using corn stover powder and solids was reported by Wang et al. (2009) in a single-chamber MFC. Lee et al. (2016) compared the performance of large two- and single-chamber MFCs using molasses wastewater (10,000 mg COD/L) operating in a continuous mode, each with a working volume of 900 mL. The single-chamber MFC achieved higher COD removal (90%) than two-chamber MFC (50%). However, the two-chamber MFC achieved a higher power density (17±10.15 mW/m^2) than the single-chamber MFC (7.9±2.56 mW/m^2). The performance of the single-chamber MFC was further evaluated for the effects of using a proton exchange membrane, and it was concluded that the membrane did not significantly impact COD removal and power generation. In addition, the study reported that methanogens existed in the reactors and contributed to 50%–90% of the COD removal. Therefore controlling methanogens in MFCs is an important operational parameter to ensure that the substrate is consumed during power production. Full-strength molasses wastewater (130,000mg COD/L) was used in a two-chamber MFC (Ali et al., 2016). The cell achieved 67% COD removal and produced a maximum power density of 242 mW/m^3. These results show that MFCs can be adequate reactors for treatment of full strength molasses wastewater.

Distillery wastewater (3200–6400mg COD/L) was used in a two-chamber MFC operated in batch mode (Samsudeen et al., 2016). The cell achieved a maximum power density of 123.5 mW/m^2, coulombic efficiency up to 27%, and COD removal up to 65%. Tanikkul and Pisutpaisal (2015) investigated the performance of a single-chamber MFC using distillery wastewater with varied COD range between 125 and 3000 mg/L. The cell

produced a maximum power density of 5.46 mW/m^3 and up to 56.7% COD removal. Recently, Deval et al. (2017) evaluated the power production and carbon degradation of anaerobically digested distillery wastewater using a two-chamber MFC. Under optimum operating conditions, the cell produced a maximum power density of 31,490 mW/m^3 and achieved up to 61% TOC reduction. The COD reduction of these studies is considered lower than conventional anaerobic methods (Pant and Adholeya, 2007). Therefore further research is needed to understand current generation and substrate utilization in MFCs using distillery wastewater.

Generally, the performance of MFCs using molasses and distillery wastewater has been obtained from lab-scale, relatively small reactors, and the performance of pilot-scale MFCs in the treatment and energy recovery from molasses and distillery wastewater still needs to be evaluated. Power densities generated from this type of wastewater are relativity low, and methanogenic control is an essential parameter in operating MFCs using this wastewater. Employing anaerobic fermentation as a pretreatment may be a viable option which can produce energy-rich hydrogen gas and further break down organic substrates to fermentation products than can be consumed by the exoelectrogenic microorganisms.

3.1.7 Seafood Industry

The seafood industry is concentrated in coastal areas where seafood processing occurs. Processing seafood produces a large amount of waste and wastewater and may have a large impact on the local community (Kosseva, 2013). Processing seafood includes fish cleaning, cooling, equipment and floor cleaning, which produce wastewater with high organics, fats, oil and grease, and nitrogen content. Literature data on the characteristics of seafood wastewater is limited. However, it has been reported that the BOD load produced from seafood-processing operation ranges between 1 and 72.5 kg per ton of product (Kosseva, 2013).

The number of studies that evaluated the use of seafood wastewater in MFCs is limited, with only four studies identified in the literature, listed in **Table 7**. You et al. (2010) evaluated the performance of anoxic/oxic MFC in the power generation and treatment of seafood wastewater in continuous mode. The hydraulic retention time (HRT) was varied between 4.2 and 16.7 h and the average COD varied between 2102 and 2522 mg/L. The largest COD removal (80.2%) was achieved at HRT of 16.7 h. However, the largest power density (16,200 mW/m^3) was achieved at HRT of 4.2 h.

The performance of small single- and two-chamber MFCs was compared using seafood wastewater with COD about 1000 mg/L (Sun, 2012). The study concluded that the single-chamber MFC produced higher power density (343.6–358.8 mW/m^2) than the two-chamber MFC (258.7–291.6 mW/m^2). Also, larger COD removal was achieved in the single-chamber MFC (85.1%) than the two-chamber MFC (64.7%). On the contrary, the two-chamber MFC achieved higher maximum coulombic efficiency (20.3%) than single-chamber MFC (14.2%). Jayashree et al. (2016) operated a continuous tubular MFC using seafood wastewater (4000 mg COD/L). The study reported power density between 105 and 222 mW/m^2 (221–886 mW/m^3) and 83% COD removal. The power densities observed from using MFC to treat seafood wastewater are promising. However, treatment efficiencies of MFCs are comparable to the efficiencies achieved by fixed film filters treating seafood wastewater which are not sufficient to be employed as a stand-alone treatment technology (Tay et al., 2006). Further research is needed to evaluate the long-term and scaled-up performance and nutrient removal from this type of wastewater.

3.1.8 Edible Oil Industry

The edible oil industry is seasonal and produces high strength wastes, with high COD (up to 220g/L), solids (up to 102.6 g total solids/L), lipids (up to 30 g/L), sugars, nitrogen, and low pH that ranges between 5 and 5.9 (Hung et al., 2005; Kosseva, 2013). Olive oil and palm oil wastewater characterization and treatment are comprehensively reviewed in Hung et al. (2005) and Yacob et al. (2005), respectively.

Several researchers have studied using oil wastewater in MFCs as summarized in **Table 8.** Palm oil mill wastewater was investigated in a two-chamber MFC but the cell did not produce significant power densities (<25 mW/m^2). Recently, Yu et al. (2017) investigated using soybean oil refinery wastewater (2900 mg COD/L) in a single-chamber MFC. The cell achieved a maximum power density of 746 mW/m^2, >96% COD removal, and up to 33.6% coulombic efficiency. An earlier study by Hamamoto et al. (2016) investigated full strength soybean oil wastewater (40 g COD/L) in a small single-chamber MFC. The cell achieved a maximum power density of 2240 mW/m^2, >77% COD removal, and up to 20% coulombic efficiency. This shows that increasing the strength of wastewater and the size of MFC can result in decreasing power density and the efficiency of the cell in removing COD.

3.2 Microbial Electrolysis Cells

Another type of BES is microbial electrolysis cell (MEC). Microbial electrolysis cells (MECs) use an external power source to catalyze the substrate into by-products, including methane (CH^4), hydrogen gas (H_2), and hydrogen peroxide (H_2O_2). While a considerable number of researchers investigated the use of MFCs to generate power from food industry waste and wastewater, the number of studies that investigated the use of MECs with this type of waste is limited. However, in some cases products produced by MEC may be more valuable than producing electricity, since these products be stored for later use or utilized in other processes. The food waste sources investigated in MECs include brewery and dairy wastewaters, molasses, animal waste, and winery wastewater, as shown in **Table 9**.

Methane production from brewery wastewater using MEC has recently been evaluated by Guo et al. (2017). The researchers used a single-chamber MEC and the average initial COD of the brewery wastewater was 1125 mg/L. The cell produced 0.14 m^3 CH_4/m^3/day and achieved a maximum COD removal of 80%. The maximum coulombic efficiency was low (32.7%) which suggests that most of the methane produced was not produced by the exoelectrogenic bacteria. Similar methane production rate was achieved in a small single-chamber MEC using soybean oil refinery wastewater of COD about 2900 mg/L (Yu et al., 2017). In their study, higher COD removal (95.8%) was achieved but the coulombic efficiency was not reported. Marone et al. (2016) evaluated different power inputs into an MEC using table olive oil processing brine wastewater as a substrate. The cell produced an average of 109 Normal mL CH_4 per g COD removed. The maximum COD removed was 29% and coulombic efficiency was 30%. Several researchers evaluated biohydrogen production using MEC, since it is a cleaner fuel than methane which can be produced by conventional anaerobic wastewater treatment methods. The coulombic efficiencies achieved by hydrogen-producing MECs are generally higher than those used for methane production. This indicates that better MECs control might be achieved if methanogens are inhibited. The performance of MECs was evaluated using various food industry wastewaters, including molasses wastewater which achieved the highest hydrogen production rate and coulombic efficiency. Wang et al. (2014) used molasses wastewater in a single-chamber MEC, and reported up to 95% coulombic efficiency, >100% cathodic energy recovery, and produced up to 10.72 m^3 H_2/m^3/day of hydrogen. The results for molasses wastewater show that MECs can be used efficiently to treat wastewater and generate biohydrogen.

Several researchers evaluated swine waste as a substrate for MECs. Wagner et al. (2009) demonstrated that using high strength swine wastewater (12,825 mg COD/L), up to 70% coulombic efficiency can be achieved, with up to 75% COD removal, and up to 1 $m^3 H_2/m^3$/day hydrogen production. Using a continuous two-chamber MEC, Sotres et al. (2015) showed that up to 54% COD reduction and 57% coulombic efficiency can be achieved using swine slurry. Cerrillo et al. (2016) compared the performance of a two-chamber MEC using swine slurry and anaerobically digested swine slurry. The MEC with undigested slurry achieved higher COD removal but lower coulombic efficiency. It was also demonstrated that up to 40% ammonia removal from the slurry could be achieved using an MEC. However, Sotres et al. (2015) and Cerrillo et al. (2016) did not report the hydrogen production from the MECs.

Cusick et al. (2010) evaluated using a lab-scale single-chamber MEC with winery wastewater (2200 mg COD/L). The MEC achieved 47% COD removal, 50% coulombic efficiency and produced 0.17 $m^3 H_2/m^3$/d. Cusick et al. (2011) tested the first pilot-scale MEC operating on winery wastewater (1000 L with 144 electrode pairs). The anodes were made of graphite fiber brushes and the cathodes were made of stainless steel mesh. The operation period of the MEC was limited by the seasonal operation of the winery (around 100 days). The cell was operated at a voltage 0.9 V, with hydraulic retention time of 1 day. The cell enrichment and inoculation took ~60 days and the wastewater was diluted to enhance the inoculations and reduce the start-up time. The start-up time was affected by temperature, pH, and VFA content of the wastewater. The maximum gas production was 0.19 m^3/m^3/day and the majority of the gas produced was methane which was against the intent of the study. The cell provided favorable conditions for methanogens growth and no inhibition or methanogen control was employed. This study demonstrated some of the challenges of scaling up MECs, which included longer start-up time than lab-scale cells and methanogenic control. Extended continuous operation could enrich methanogens, as was also reported by other studies (Rader and Logan, 2010).

4 Limitations and Challenges of BESs

Bioelectrochemical systems are unique systems that have the potential to recover energy and treat wastes. Over the past two decades, the growth of published research on BESs has been exponential (Aghababaie et al., 2015; Wang et al., 2015). The efforts of recovering energy while treating

food waste have been dominated by microbial fuel cells as compared to other BESs. Despite the significant efforts in developing bioelectrochemical systems, there are still key limitations and challenges facing bioelectrochemical systems, as presented in this chapter for both microbial fuel cells and microbial electrolysis cells.

The cathode is the limiting electrode in a microbial fuels cell, and to enhance the performance a catalyst is traditionally used. There has been significant research effort applied in testing materials that are suitable for MFCs, with platinum (Pt) catalyst being among the most widely used. However, Pt is an expensive metal which increases the cost of constructing MFCs. Furthermore, the use of ion membrane in actual wastewater makes it susceptible to fouling which greatly increases the internal resistance of the cell and reduces the electric current. Similar challenges and limitations have been identified for MECs. Electron losses increase the required power input to the system, and methanogenic inhibition is also essential for controlling the system during operation.

Microbial fuel cells are devices that produce power while treating waste. The power produced in microbial fuels cells is lower than the theoretical power due to electron losses. Many factors contribute to electron losses in the cell including resistance to electron flow through the electrodes, connections, and membrane; activation energy needed to for redox reactions; losses in the bacterium; and losses due to concentration gradient (Logan et al., 2006). The sum of these losses in an MFC contributes to limiting the current produced. Furthermore, the power production is limited by microbial growth, substrate diffusion into the biofilm, and conversion of substrates in the cell environment. The coulombic efficiency of the cell is limited by the microbial culture in the cell and substrate. Substrate conversion is also limited by the substrate concentrations; high concentrations of substrate and low pH levels may inhibit exoelectrogenic activity (Kim and Logan, 2011; Lin et al., 2016; Rikame et al., 2012). In addition, higher concentrations of metals and toxins may inhibit microbial activity.

The optimum operation conditions of microbial fuels cells are close to the optimum conditions of methanogenesis. Therefore in continuous long-term operation of microbial fuel cells, methanogenic control is essential. In batch operation of MFC, methanogens are inhibited by the aeration of the electrodes between the batches. In continuous operation of MFC, some cells achieved high substrate reduction while low coulombic efficiency was achieved. This indicated that the substrate went through the fermentation and methanogenetic pathways and the electrons from the redox reactions were not transferred into the electrodes. Some substrates

may provide inhibitory conditions to methanogens, like winery and brewery wastewaters, which have low pH levels.

As demonstrated in the latter studies, the performance of the lab-scaled units cannot readily be extrapolated to commercially relevant sizes (Cusick et al., 2011; Hiegemann et al., 2016). Conventional anaerobic processes are sized according to the HRT needed to achieve the required degree of treatment, while BESs are also limited by the power production in addition to HRT. Low electric current and coulombic efficiencies are achieved in scaled-up systems which make the footprint large, even to power a small electronic device (Sun et al., 2016). Voltage reversal is also one of the factors that contributes to the electric current reduction in scaled-up systems. The substrate removal of scaled-up MFCs is not sufficient to operate MFCs as a sole unit process for waste treatment. It is envisioned that BESs can be a unit process within a waste treatment scheme. Furthermore, the internal resistance of scaled-up systems is increased which results in reducing electric current. Scaling up BESs also increases the start-up time of the systems, and COD reduction in scaled-up BESs generally takes longer.

5 Future Perspective and Research Needs

Bioelectrochemical systems is a promising technology that has the potential to recover resources, energy, and treat waste. With the expanding need to recover resources, secure the food supply, and maintain a clean and healthy environment, development of systems like BESs is essential. While in the food industry, anaerobic digestion is mostly used to recover energy and treat food wastes, BESs can be advantageous since they can be operated at the ambient wastewater temperature and do not require precise temperature control. In addition, BESs can be compacted and costumed to different shapes that can be installed inside buildings.

Over the past two decades, there have been great efforts to understand and optimize the performance of these systems. The effort has focused on optimizing lab-scale architecture, materials, and performance using both synthetic and actual wastewater. However, there is still need for more research to optimize scaled-up systems, increase power and current, reduce internal resistance for the entire system, increase efficiencies, and reduce the system footprint.

The investigation of new materials and reactor configuration is likely to continue, especially to reduce costs and discover cheaper catalysts. Further research is needed to better understand the electron transport from

the microbes to the electrodes. Optimizing BESs by enhancing transport through the ion exchange membrane, improved fundamental understanding through mathematical modeling, and discovery of cheaper materials with comparable performance are needed. Like anaerobic biological processes, BESs operate optimally at around neutral pH and are sensitive to shock loadings. Therefore an equalization basin with pH adjustment might be needed in the process stream before the BES. However, there is still research needed to evaluate the long-term performance of continuous systems and their tolerance to changing environments.

Application of the BESs for purposes other than waste treatment requires further investigation. MFCs produce electrical current from organic substrates, and so they can be used as real-time sensors for substrates in various environments. MECs are suitable for generation of products onsite and can be incorporated in different industrial applications. The use of hybrid systems, which synergistically use multiple groups of microorganisms such as microalgae and bacteria, to optimize performance and treatment is also a promising approach. The performance of BESs in catalyzing organic carbon-based substrates is limited by the volatile fatty acids concentrations in the substrate. Therefore coupling BESs with anaerobic fermentation is still a promising strategy, especially for high strength wastewater.

The cost of membrane filters has been decreasing in recent years, and the combination of membrane filters with BESs in a continuous and recycling operation scheme may allow for the use of pure cultures that are known to produce higher current. Concentrations of nitrogen, phosphorus, and sulfur-based chemicals can be high in food wastes, especially meat-based wastes. Studies have shown that BESs have a promising ability to remove nitrogen and phosphorus from wastewater. Further research is still needed to optimize this approach and achieve a better understanding of the kinetics and pathways of nitrogen and phosphorus removal.

6 Conclusions

The efficiency of microbial fuel cells and microbial electrolysis cells in treating food wastes was reviewed. Bioelectrochemical systems are still in their infancy and further research is needed to better understand the systems and optimize their performance. Microbial fuel cells have been the focus of researchers for food industry waste and wastewater treatment due to their capability to produce electricity. Fewer researchers have

investigated microbial electrolysis cells. Among the food waste investigated, brewery and sugar-based wastewater hold the most promise for higher power density generation from MFC. Other waste sources may have better performance if coupled with fermentation as a pretreatment process. Scaled-up systems using food waste have not been extensively evaluated. Several limitations and challenges are discussed including reduction of performance in scaled-up systems, treatment efficiency, electron loss, and internal resistance of the systems. The control of methanogenic microbes is essential, especially for continuous long-term operation. Further research on the removal of sulfur-based compounds from actual food wastewater using bioelectrochemical systems is needed.

References

Abbasi, U., Jin, W., Pervez, A., Bhatti, Z.A., Tariq, M., Shaheen, S., Iqbal, A., Mahmood, Q., 2016. Anaerobic microbial fuel cell treating combined industrial wastewater: correlation of electricity generation with pollutants. Bioresour. Technol. 200, 1–7. doi 10.1016/j.biortech.2015.09.088.

Abreu, M.A., Toffoli, S.M., 2009. Characterization of a chromium-rich tannery waste and its potential use in ceramics. Ceram. Int. 35, 2225–2234. doi 10.1016/j.ceramint.2008.12.011.

Aghababaie, M., Farhadian, M., Jeihanipour, A., Biria, D., 2015. Effective factors on the performance of microbial fuel cells in wastewater treatment—a review. Environ. Technol. Rev. 4, 71–89. doi 10.1080/09593330.2015.1077896.

Algino, R.J., Ingham, S.C., Zhu, J., 2007. Survey of antimicrobial effects of beef carcass intervention treatments in very small state-inspected slaughter plants. J. Food Sci. 72, M173–M179. doi 10.1111/j.1750-3841.2007.00386.x.

Ali, N., Yousaf, S., Anam, M., Bangash, Z., Maleeha, S., 2016. Evaluating the efficiency of a mixed culture biofilm for the treatment of black liquor and molasses in a mediator-less microbial fuel cell. Environ. Technol. 37, 2815–2822. doi 10.1080/09593330.2016.1166267.

Angosto, J.M., Fernández-López, J.A., Godínez, C., 2015. Brewery and liquid manure wastewaters as potential feedstocks for microbial fuel cells: a performance study. Environ. Technol. 36, 68–78. doi 10.1080/09593330.2014.937769.

Angulo, J., Mahecha, L., Yepes, S.A., Yepes, A.M., Bustamante, G., Jaramillo, H., Valencia, E., Villamil, T., Gallo, J., 2012. Quantitative and nutritional characterization of fruit and vegetable waste from marketplace: a potential use as bovine feedstuff? J. Environ. Manag. 95, 203–209. doi 10.1016/j.jenvman.2010.09.022.

Bajracharya, S., ElMekawy, A., Srikanth, S., Pant, D., 2016. Cathodes for microbial fuel cells. In: Scott, K., Yu, E.H. (Eds.), Microbial Electrochemical and Fuel Cells: Fundamentals and Applications. Woodhead Publishing is an imprint of Elsevier, Cambridge, UK, pp. 179–213.

Banks, C., Wang, Z., 2005. Treatment of meat wastes. In: Wang, L.K., Hung, Y.-T., Lo, H.H., Yapijakis, C. (Eds.), Waste Treatment in the Food Processing Industry. CRC Press, Boca Raton, FL, pp. 67–100.

Baranitharan, E., Khan, M.R., Prasad, D.M.R., Teo, W.F.A., Tan, G.Y.A., Jose, R., 2015. Effect of biofilm formation on the performance of microbial fuel cell for the treatment of palm oil mill effluent. Bioprocess Biosyst. Eng. 38, 15–24. doi 10.1007/s00449-014-1239-9.

Boghani, H., Kim, J.R., Dinsdale, R.M., Guwy, A.J., Premier, G.C., 2017. Reducing the burden of food processing washdown wastewaters using microbial fuel cells. Biochem. Eng. J. 117, 210–217. doi 10.1016/j.bej.2016.10.017.

Boone, D.R., 1982. Terminal reactions in the anaerobic digestion of animal waste. Appl. Environ. Microbiol. 43, 57–64.

Bouallagui, H., Cheikh, R.B., Marouani, L., Hamdi, M., 2003. Mesophilic biogas production from fruit and vegetable waste in a tubular digester. Bioresour. Technol. 86, 85–89. doi 10.1016/s0960-8524(02)00097-4.

Britz, T.J., van Schalkwyk, C., 2005. Treatment of dairy processing wastewaters. In: Wang, L.K., Hung, Y.-T., Lo, H.H., Yapijakis, C. (Eds.), Waste Treatment in the Food Processing Industry. CRC Press, Boca Raton, FL, pp. 1–24.

Call, D., Logan, B.E., 2008. Hydrogen production in a single chamber microbial electrolysis cell lacking a membrane. Environ. Sci. Technol. 42, 3401–3406. doi 10.1021/es8001822.

Cao, X., Huang, X., Liang, P., Xiao, K., Zhou, Y., Zhang, X., Logan, B.E., 2009. A new method for water desalination using microbial desalination cells. Environ. Sci. Technol. 43, 7148–7152. doi 10.1021/es901950j.

Caro, D., Davis, S.J., Bastianoni, S., Caldeira, K., 2017. Greenhouse gas emissions due to meat production in the last fifty years. In: Ahmed, M., Stockle, C.O. (Eds.), Quantification of Climate Variability, Adaptation and Mitigation for Agricultural Sustainability. Springer International Publishing, Switzerland, pp. 27–37.

Cercado, B., Vega-Guerrero, A.L., Rodríguez-Valadez, F., Hernández-López, J.L., Cházaro-Ruiz, L.F., Délia, M.L., Bergel, A., 2014. Carbonaceous and protein constituents in dairy wastewater lead to a differentiated current generation in microbial fuel cells (MFCs). J. Mex. Chem. Soc. 58, 309–314.

Cercado-Quezada, B., Delia, M.-L., Bergel, A., 2010a. Testing various food-industry wastes for electricity production in microbial fuel cell. Bioresour. Technol. 101, 2748–2754. doi 10.1016/j.biortech.2009.11.076.

Cercado-Quezada, B., Delia, M.-L., Bergel, A., 2010b. Treatment of dairy wastes with a microbial anode formed from garden compost. J. Appl. Electrochem. 40, 225–232. doi 10.1007/s10800-009-0001-5.

Cerrillo, M., Oliveras, J., Viñas, M., Bonmatí, A., 2016. Comparative assessment of raw and digested pig slurry treatment in bioelectrochemical systems. Bioelectrochemistry 110, 69–78. doi 10.1016/j.bioelechem.2016.03.004.

Çetinkaya, A.Y., Köroğlu, E.O., Demir, N.M., Baysoy, D.Y., Özkaya, B., Çakmakçı, M., 2015. Electricity production by a microbial fuel cell fueled by brewery wastewater and the factors in its membrane deterioration. Chin. J. Catal. 36, 1068–1076. doi 10.1016/s1872-2067(15)60833-6.

Chandrasekhar, K., Amulya, K., Mohan, S.V., 2015. Solid phase bio-electrofermentation of food waste to harvest value-added products associated with waste remediation. Waste Manag. 45, 57–65. doi 10.1016/j.wasman.2015.06.001.

Cheng, S., Xing, D., Logan, B.E., 2011. Electricity generation of single-chamber microbial fuel cells at low temperatures. Biosens. Bioelectron. 26, 1913–1917. doi 10.1016/j.bios.2010.05.016.

Choi, J., Ahn, Y., 2015. Enhanced bioelectricity harvesting in microbial fuel cells treating food waste leachate produced from biohydrogen fermentation. Bioresour. Technol. 183, 53–60. doi 10.1016/j.biortech.2015.01.109.

Choi, J., Chang, H.N., Han, J.-I., 2011. Performance of microbial fuel cell with volatile fatty acids from food wastes. Biotechnol. Lett. 33, 705–714. doi 10.1007/s10529-010-0507-2.

Christwardana, M., Prabowo, A.K., Tiarasukma, A.P., Ariyanti, D., 2016. Microbial fuel cells for simultaneous electricity generation and organic degradation from slaughterhouse wastewater. Int. J. Renew. Energy Dev. 5, 107–112. doi 10.14710/ijred.5.2.107-112.

Crawford, G., 2007. In: Managing sulfur concentrations in feed and water. Minnesota Nutrition Conference.

Cusick, R.D., Kiely, P.D., Logan, B.E., 2010. A monetary comparison of energy recovered from microbial fuel cells and microbial electrolysis cells fed winery or domestic wastewaters. Int. J. Hydrog. Energy 35, 8855–8861. doi 10.1016/j.ijhydene.2010.06.077.

Cusick, R.D., Bryan, B., Parker, D.S., Merrill, M.D., Mehanna, M., Kiely, P.D., Liu, G., Logan, B.E., 2011. Performance of a pilot-scale continuous flow microbial electrolysis cell fed winery wastewater. Appl. Microbiol. Biotechnol. 89, 2053–2063. doi 10.1007/s00253-011-3130-9.

Danalewich, J.R., Papagiannis, T.G., Belyea, R.L., Tumbleson, M.E., Raskin, L., 1998. Characterization of dairy waste streams, current treatment practices, and potential for biological nutrient removal. Water Res. 32, 3555–3568. doi 10.1016/s0043-1354(98)00160-2.

de Vries, M., de Boer, I.J.M., 2010. Comparing environmental impacts for livestock products: a review of life cycle assessments. Livest. Sci. 128, 1–11. doi 10.1016/j.livsci.2009.11.007.

Demirel, B., Yenigun, O., Onay, T.T., 2005. Anaerobic treatment of dairy wastewaters: a review. Process Biochem. 40, 2583–2595. doi 10.1016/j.procbio.2004.12.015.

Deval, A.S., Parikh, H.A., Kadier, A., Chandrasekhar, K., Bhagwat, A.M., Dikshit, A.K., 2017. Sequential microbial activities mediated bioelectricity production from distillery wastewater using bio-electrochemical system with simultaneous waste remediation. Int. J. Hydrog. Energy 42, 1130–1141. doi 10.1016/j.ijhydene.2016.11.114.

Ditzig, J., Liua, H., Logan, B.E., 2007. Production of hydrogen from domestic wastewater using a bioelectrochemically assisted microbial reactor (BEAMR). Int. J. Hydrog. Energy 32, 2296–2304. doi 10.1016/j.ijhydene.2007.02.035.

Du, H., Li, F., 2016. Size effects of potato waste on its treatment by microbial fuel cell. Environ. Technol. 37, 1305–1313. doi 10.1080/09593330.2015.1114027.

Du, Z., Li, H., Gu, T., 2007. A state of the art review on microbial fuel cells: a promising technology for wastewater treatment and bioenergy. Biotechnol. Adv. 25, 464–482. doi 10.1016/j.biotechadv.2007.05.004.

Dumitru, A., Scott, K., 2016. Anode materials for microbial fuel cells. In: Scott, K., Yu, E.H. (Eds.), Microbial Electrochemical and Fuel Cells: Fundamentals and Applications. Woodhead Publishing is an imprint of Elsevier, Cambridge, UK, pp. 117–152.

Durruty, I., Bonanni, P.S., González, J.F., Busalmen, J.P., 2012. Evaluation of potato-processing wastewater treatment in a microbial fuel cell. Bioresour. Technol. 105, 81–87. doi 10.1016/j.biortech.2011.11.095.

Egbadon, E.O., Akujobi, C.O., Nweke, C.O., Braide, W., Akaluka, C.K., Adeleye, S.A., 2016. Simultaneous generation of bioelectricity and treatment of swine wastewater in a microbial fuel cell. Int. Lett. Nat. Sci. 54, 100–107. doi 10.18052/www.scipress.com/ilns.54.100.

Elakkiya, E., Matheswaran, M., 2013. Comparison of anodic metabolisms in bioelectricity production during treatment of dairy wastewater in microbial fuel cell. Bioresour. Technol. 136, 407–412. doi 10.1016/j.biortech.2013.02.113.

ElMekawy, A., Srikanth, S., Bajracharya, S., Hegab, H.M., Nigam, P.S., Singh, A., Mohan, S.V., Pant, D., 2015. Food and agricultural wastes as substrates for bioelectrochemical system (BES): the synchronized recovery of sustainable energy and waste treatment. Food Res. Int. 73, 213–225. doi 10.1016/j.foodres.2014.11.045.

Escapa, A., Gil-Carrera, L., García, V., Morán, A., 2012. Performance of a continuous flow microbial electrolysis cell (MEC) fed with domestic wastewater. Bioresour. Technol. 117, 55–62. doi 10.1016/j.biortech.2012.04.060.

Estrada-Arriaga1, E.B., García-Sánchez, L., Garzón-Zuñiga, M.A., González-Rodríguez, J.G., 2015. Utilization of microbial fuel cells for the treatment of wastewater from a pig farm. Fresenius Environ. Bull. 24, 2512–2518.

Faria, A., Gonçalves, L., Peixoto, J.M., Peixoto, L., Brito, A.G., Martins, G., 2017. Resources recovery in the dairy industry: bioelectricity production using a continuous microbial fuel cell. J. Clean. Prod. 140, 971–976. doi 10.1016/j.jclepro.2016.04.027.

Feng, Y., Wang, X., Logan, B.E., Lee, H., 2008. Brewery wastewater treatment using air-cathode microbial fuel cells. Appl. Microbiol. Biotechnol. 78, 873–880. doi 10.1007/s00253-008-1360-2.

Goud, R.K., Babu, P.S., Mohan, S.V., 2011. Canteen based composite food waste as potential anodic fuel for bioelectricity generation in single chambered microbial fuel cell (MFC): bio-electrochemical evaluation under increasing substrate loading condition. Int. J. Hydrog. Energy 36, 6210–6218. doi 10.1016/j.ijhydene.2011.02.056.

Guo, Z., Thangavel, S., Wang, L., He, Z., Cai, W., Wang, A., Liu, W., 2017. Efficient methane production from beer wastewater in a membraneless microbial electrolysis cell with a stacked cathode: the effect of the cathode/anode ratio on bioenergy recovery. Energy Fuel 31, 615–620. doi 10.1021/acs.energyfuels.6b02375.

Hamamoto, K., Miyahara, M., Kouzuma, A., Matsumoto, A., Yoda, M., Ishiguro, T., Watanabe, K., 2016. Evaluation of microbial fuel cells for electricity generation from oil-contaminated wastewater. J. Biosci. Bioeng. 122, 589–593. doi 10.1016/j.jbiosc.2016.03.025.

Heilmann, J., Logan, B.E., 2006. Production of electricity from proteins using a microbial fuel cell. Water Environ. Res. 78, 531–537. doi 10.2175/106143005x73046.

Hiegemann, H., Herzer, D., Nettmann, E., Lübken, M., Schulte, P., Schmelz, K.-G., Gredigk-Hoffmann, S., Wichern, M., 2016. An integrated 45L pilot microbial fuel cell system at a full-scale wastewater treatment plant. Bioresour. Technol. 218, 115–122. doi 10.1016/j.biortech.2016.06.052.

Hou, Q., Pei, H., Hu, W., Jiang, L., Yu, Z., 2016. Mutual facilitations of food waste treatment, microbial fuel cell bioelectricity generation and Chlorella vulgaris lipid production. Bioresour. Technol. 203, 50–55. doi 10.1016/j.biortech.2015.12.049.

Hung, Y.-T., Salman, H., Awad, A., 2005. Olive oil waste treatment. In: Wang, L.K., Hung, Y.-T., Lo, H.H., Yapijakis, C. (Eds.), Waste Treatment in the Food Processing Industry. CRC Press, Boca Raton, FL, pp. 119–192.

Ichihashi, O., Hirooka, K., 2012. Removal and recovery of phosphorus as struvite from swine wastewater using microbial fuel cell. Bioresour. Technol. 114, 303–307. doi 10.1016/j.biortech.2012.02.124.

Ismail, Z.Z., Mohammed, A.J., 2016. Biotreatment of slaughterhouse wastewater accompanied with sustainable electricity generation in microbial fuel cell. Syst. Cybertnetics Informatics 14, 30–35.

Jadhav, D.A., Jain, S.C., Ghangrekar, M.M., 2016. Cow's urine as a yellow gold for bioelectricity generation in low cost clayware microbial fuel cell. Energy 113, 76–84. doi 10.1016/j.energy.2016.07.025.

Jayashree, C., Janshi, G., Yeom, I.T., Kumar, S.A., Banu, J.R., 2014. Effect of low temperature thermo-chemical pretreatment of dairy waste activated sludge on the performance of microbial fuel cell. Int. J. Electrochem. Sci. 9, 5732–5742.

Jayashree, C., Tamilarasan, K., Rajkumar, M., Arulazhagan, P., Yogalakshmi, K.N., Srikanth, M., Banu, J.R., 2016. Treatment of seafood processing wastewater using upflow microbial fuel cell for power generation and identification of bacterial community in anodic biofilm. J. Environ. Manag. 180, 351–358. doi 10.1016/j.jenvman.2016.05.050.

Jia, Y.H., Choi, J.Y., Ryu, J.H., Kim, C.H., Lee, W.K., Tran, H.T., Zhang, R.H., Ahn, D.H., 2010. Hydrogen production from wastewater using a microbial electrolysis cell. Korean J. Chem. Eng. 27, 1854–1859. doi 10.1007/s11814-010-0310-8.

Jia, J., Tang, Y., Liu, B., Wu, D., Ren, N., Xing, D., 2013. Electricity generation from food wastes and microbial community structure in microbial fuel cells. Bioresour. Technol. 144, 94–99. doi 10.1016/j.biortech.2013.06.072.

Kiely, P.D., Cusick, R., Call, D.F., Selembo, P.A., Regan, J.M., Logan, B.E., 2011a. Anode microbial communities produced by changing from microbial fuel cell to microbial electrolysis cell operation using two different wastewaters. Bioresour. Technol. 102, 388–394. doi 10.1016/j.biortech.2010.05.019.

Kiely, P.D., Regan, J.M., Logan, B.E., 2011b. The electric picnic: synergistic requirements for exoelectrogenic microbial communities. Curr. Opin. Biotechnol. 22, 378–385. doi 10.1016/j.copbio.2011.03.003.

Kim, Y., Logan, B.E., 2011. Hydrogen production from inexhaustible supplies of fresh and salt water using microbial reverse-electrodialysis electrolysis cells. Proc. Natl. Acad. Sci. 108, 16176–16181. doi 10.1073/pnas.1106335108.

Kim, J.R., Dec, J., Bruns, M.A., Logan, B.E., 2008. Removal of odors from swine wastewater by using microbial fuel cells. Appl. Environ. Microbiol. 74, 2540–2543. doi 10.1128/aem.02268-07.

Kim, K.-Y., Yang, W., Evans, P.J., Logan, B.E., 2016. Continuous treatment of high strength wastewaters using air-cathode microbial fuel cells. Bioresour. Technol. 221, 96–101. doi 10.1016/j.biortech.2016.09.031.

Kosseva, M.R., 2013. Sources, characterization, and composition of food industry wastes. In: Kosseva, M., Webb, C. (Eds.), Food Industry Wastes—Assessment and Recuperation of Commodities. Elsevier, London, UK, pp. 37–60. doi 10.1016/B978-0-12-391921-2.00003-2.

Kumar, R., Singh, L., Zularisam, A.W., 2015. Bioelectricity generation and treatment of sugar mill effluent using a microbial fuel cell. J. Clean Energy Technol. 4, 249–252. doi 10.7763/jocet.2016.v4.291.

Lee, Y.-Y., Kim, T.G., Cho, K.-S., 2016. Characterization of the COD removal, electricity generation, and bacterial communities in microbial fuel cells treating molasses wastewater. J. Environ. Sci. Health Part A 51, 1131–1138. doi 10.1080/10934529.2016.1199926.

Leech, D., Kavanagh, P., Schuhmann, W., 2012. Enzymatic fuel cells: recent progress. Electrochim. Acta 84, 223–234. doi 10.1016/j.electacta.2012.02.087.

Li, X.M., Cheng, K.Y., Wong, J.W.C., 2013. Bioelectricity production from food waste leachate using microbial fuel cells: effect of NaCl and pH. Bioresour. Technol. 149, 452–458. doi 10.1016/j.biortech.2013.09.037.

Li, H., Tian, Y., Zuo, W., Zhang, J., Pan, X., Li, L., Su, X., 2016. Electricity generation from food wastes and characteristics of organic matters in microbial fuel cell. Bioresour. Technol. 205, 104–110. doi 10.1016/j.biortech.2016.01.042.

Li, S.-W., He, H., Zeng, R.J., Sheng, G.-P., 2017. Chitin degradation and electricity generation by *Aeromonas hydrophila* in microbial fuel cells. Chemosphere 168, 293–299. doi 10.1016/j.chemosphere.2016.10.080.

Liakos, T.I., Sotiropoulos, S., Lazaridis, N.K., 2017. Electrochemical and bio-electrochemical treatment of baker's yeast effluents. J. Environ. Chem. Eng. 5, 699–708. doi 10.1016/j.jece.2016.12.048.

Lim, S.J., Park, W., Kim, T.-H., Shin, I.H., 2012. Swine wastewater treatment using a unique sequence of ion exchange membranes and bioelectrochemical system. Bioresour. Technol. 118, 163–169. doi 10.1016/j.biortech.2012.05.021.

Lin, H., Wu, X., Nelson, C., Miller, C., Zhu, J., 2016. Electricity generation and nutrients removal from high-strength liquid manure by air-cathode microbial fuel cells. J. Environ. Sci. Health Part A 51, 240–250. doi 10.1080/10934529.2015.1094342.

Liu, J., Zhang, F., He, W., Zhang, X., Feng, Y., Logan, B.E., 2014. Intermittent contact of fluidized anode particles containing exoelectrogenic biofilms for continuous power generation in microbial fuel cells. J. Power Sources 261, 278–284. doi 10.1016/j.jpowsour.2014.03.071.

Logan, B., 2008. Microbial Fuel Cells. John Wiley & Sons, Inc., Hoboken, NJ.

Logan, B.E., 2009. Exoelectrogenic bacteria that power microbial fuel cells. Nat. Rev. Microbiol. 7, 375–381. doi 10.1038/nrmicro2113.

Logan, B.E., Hamelers, B., Rozendal, R., Schröder, U., Keller, J., Freguia, S., Aelterman, P., Verstraete, W., Rabaey, K., 2006. Microbial fuel cells: methodology and technology. Environ. Sci. Technol. 40, 5181–5192. doi 10.1021/es0605016.

Logan, B.E., Wallack, M.J., Kim, K.-Y., He, W., Feng, Y., Saikaly, P.E., 2015. Assessment of microbial fuel cell configurations and power densities. Environ. Sci. Technol. Lett. 2, 206–214. doi 10.1021/acs.estlett.5b00180.

Ma, J., Ni, H., Su, D., Meng, X., 2016. Bioelectricity generation from pig farm wastewater in microbial fuel cell using carbon brush as electrode. Int. J. Hydrog. Energy 41, 16191–16195. doi 10.1016/j.ijhydene.2016.05.255.

Mansoorian, H.J., Mahvi, A.H., Jafari, A.J., Amin, M.M., Rajabizadeh, A., Khanjani, N., 2013. Bioelectricity generation using two chamber microbial fuel cell treating wastewater from food processing. Enzym. Microb. Technol. 52, 352–357. doi 10.1016/j.enzmictec.2013.03.004.

Mansoorian, H.J., Mahvi, A.H., Jafari, A.J., Khanjani, N., 2016. Evaluation of dairy industry wastewater treatment and simultaneous bioelectricity generation in a catalyst-less and mediator-less membrane microbial fuel cell. J. Saudi Chem. Soc. 20, 88–100. doi 10.1016/j.jscs.2014.08.002.

Marone, A., Carmona-Martínez, A.A., Sire, Y., Meudec, E., Steyer, J.P., Bernet, N., Trably, E., 2016. Bioelectrochemical treatment of table olive brine processing wastewater for biogas production and phenolic compounds removal. Water Res. 100, 316–325. doi 10.1016/j.watres.2016.05.008.

Meignanalakshmi, S., Kumar, S.V., 2016. Bioelectricity production by using goat (*Capra hircus*) rumen fluid from slaughterhouse waste in mediator-less microbial fuel cells. Energy Sources, Part A Recover. Util. Environ. Eff. 38, 1364–1369. doi 10.1080/15567036.2014.907846.

Min, B., Kim, J., Oh, S., Regan, J.M., Logan, B.E., 2005. Electricity generation from swine wastewater using microbial fuel cells. Water Res. 39, 4961–4968. doi 10.1016/j.watres.2005.09.039.

Miner, J.R., 1976. Production and Transport of Gaseous NH_3 and H_2S Associated with Livestock Production. Environmental Protection Agency, Office of Research and Development, Robert S. Kerr Environmental Research Laboratory.

Miran, W., Nawaz, M., Kadam, A., Shin, S., Heo, J., Jang, J., Lee, D.S., 2015. Microbial community structure in a dual chamber microbial fuel cell fed with brewery waste for azo dye degradation and electricity generation. Environ. Sci. Pollut. Res. 22, 13477–13485. doi 10.1007/s11356-015-4582-8.

Mohamed, H.O., Obaid, M., Khalil, K.A., Barakat, N.A.M., 2016. Power generation from unconditioned industrial wastewaters using commercial membranes-based microbial fuel cells. Int. J. Hydrog. Energy 41, 4251–4263. doi 10.1016/j.ijhydene.2016.01.022.

Mohan, S.V., Chandrasekhar, K., 2011. Solid phase microbial fuel cell (SMFC) for harnessing bioelectricity from composite food waste fermentation: influence of electrode assembly and buffering capacity. Bioresour. Technol. 102, 7077–7085. doi 10.1016/j.biortech.2011.04.039.

Mohan, S.V., Mohanakrishna, G., Sarma, P.N., 2010a. Composite vegetable waste as renewable resource for bioelectricity generation through noncatalyzed open-air cathode microbial fuel cell. Bioresour. Technol. 101, 970–976. doi 10.1016/j.biortech.2009.09.005.

Mohan, S.V., Mohanakrishna, G., Velvizhi, G., Babu, V.L., Sarma, P.N., 2010b. Bio-catalyzed electrochemical treatment of real field dairy wastewater with simultaneous power generation. Biochem. Eng. J. 51, 32–39. doi 10.1016/j.bej.2010.04.012.

Montpart, N., Rago, L., Baeza, J.A., Guisasola, A., 2015. Hydrogen production in single chamber microbial electrolysis cells with different complex substrates. Water Res. 68, 601–615. doi 10.1016/j.watres.2014.10.026.

Moreno, R., Escapa, A., Cara, J., Carracedo, B., Gómez, X., 2015. A two-stage process for hydrogen production from cheese whey: integration of dark fermentation and biocatalyzed electrolysis. Int. J. Hydrog. Energy 40, 168–175. doi 10.1016/j.ijhydene.2014.10.120.

Mshoperi, E., Fogel, R., Limson, J., 2014. Application of carbon black and iron phthalocyanine composites in bioelectricity production at a brewery wastewater fed microbial fuel cell. Electrochim. Acta 128, 311–317. doi 10.1016/j.electacta.2013.11.016.

Nasirahmadi, S., Safekordi, A.A., 2011. Whey as a substrate for generation of bioelectricity in microbial fuel cell using E. coli. Int. J. Environ. Sci. Technol. 8, 823–830. doi 10.1007/bf03326265.

Naylor, R., Steinfeld, H., Falcon, W., Galloway, J., Smil, V., Bradford, E., Alder, J., Mooney, H., 2005. Agriculture: losing the links between livestock and land. Science 310, 1621–1622. doi 10.1126/science.1117856.

Nevin, K.P., Woodard, T.L., Franks, A.E., Summers, Z.M., Lovley, D.R., 2010. Microbial electrosynthesis: feeding microbes electricity to convert carbon dioxide and water to multicarbon extracellular organic compounds. MBio. 1. doi 10.1128/mbio.00103-10.

Oh, S., Logan, B.E., 2005. Hydrogen and electricity production from a food processing wastewater using fermentation and microbial fuel cell technologies. Water Res. 39, 4673–4682. doi 10.1016/j.watres.2005.09.019.

Pandey, P., Shinde, V.N., Deopurkar, R.L., Kale, S.P., Patil, S.A., Pant, D., 2016. Recent advances in the use of different substrates in microbial fuel cells toward wastewater treatment and simultaneous energy recovery. Appl. Energy 168, 706–723. doi 10.1016/j.apenergy.2016.01.056.

Pant, D., Adholeya, A., 2007. Biological approaches for treatment of distillery wastewater: a review. Bioresour. Technol. 98, 2321–2334. doi 10.1016/j.biortech.2006.09.027.

Pant, D., Van Bogaert, G., Alvarez-Gallego, Y., Diels, L., Vanbroekhoven, K., 2016. Evaluation of bioelectrogenic potential of four industrial effluents as substrate for low cost microbial fuel cells operation. Environ. Eng. Manag. J. 15, 1897–1904.

Pekan, G., Koksal, E., Küçükerdönmez, Ö., Özel, H., 2006. Household Food Wastage in Turkey. Food and Agriculture Organization of the United Nations.

Penteado, E.D., Fernandez-Marchante, C.M., Zaiat, M., Cañizares, P., Gonzalez, E.R., Rodrigo, M.A., 2016a. Influence of sludge age on the performance of MFC treating winery wastewater. Chemosphere 151, 163–170. doi 10.1016/j.chemosphere.2016.01.030.

Penteado, E.D., Fernandez-Marchante, C.M., Zaiat, M., Cañizares, P., Gonzalez, E.R., Rodrigo, M.A., 2016b. Energy recovery from winery wastewater using a dual chamber microbial fuel cell. J. Chem. Technol. Biotechnol. 91, 1802–1808. doi 10.1002/jctb.4771.

Philips, J., Verbeeck, K., Rabaey, K., Arends, J.B.A., 2016. Electron transfer mechanisms in biofilms. In: Scott, K., Yu, E.H. (Eds.), Microbial Electrochemical and Fuel Cells: Fundamentals and Applications. Woodhead Publishing is an Imprint of Elsevier, pp. 67–113.

Pisutpaisal, N., Sirisukpoca, U., 2012. Bioelectricity generation from wastewaters in microbial fuel cells. Adv. Mater. Res. 512–515, 1456–1460. doi 10.4028/www.scientific.net/amr.512-515.1456.

Potter, M.C., 1911. Electrical effects accompanying the decomposition of organic compounds. Proc. R. Soc. B Biol. Sci. 84, 260–276. doi 10.1098/rspb.1911.0073.

Rabaey, K., Verstraete, W., 2005. Microbial fuel cells: novel biotechnology for energy generation. Trends Biotechnol. 23, 291–298. doi 10.1016/j.tibtech.2005.04.008.

Rabaey, K., Clauwaert, P., Aelterman, P., Verstraete, W., 2005. Tubular microbial fuel cells for efficient electricity generation. Environ. Sci. Technol. 39, 8077–8082. doi 10.1021/es050986.

Rabaey, K., Van de Sompel, K., Maignien, L., Boon, N., Aelterman, P., Clauwaert, P., De Schamphelaire, L., Pham, H.T., Vermeulen, J., Verhaege, M., Lens, P., Verstraete, W., 2006. Microbial fuel cells for sulfide removal. Environ. Sci. Technol. 40, 5218–5224. doi 10.1021/es060382u.

Rader, G.K., Logan, B.E., 2010. Multi-electrode continuous flow microbial electrolysis cell for biogas production from acetate. Int. J. Hydrog. Energy 35, 8848–8854. doi 10.1016/j.ijhydene.2010.06.033.

Rago, L., Baeza, J.A., Guisasola, A., 2017. Bioelectrochemical hydrogen production with cheese whey as sole substrate. J. Chem. Technol. Biotechnol. 92, 173–179. doi 10.1002/jctb.4987.

Rasep, Z., Aripen, N.S.M., Ghazali, M.S.M., Yahya, N., Arida, A.S., Som, A.M., Mustaza, M.F., 2016. Microbial fuel cell for conversion of chemical energy to electrical energy from food industry wastewater. J. Environ. Sci. Technol. 9, 481–485. doi 10.3923/jest.2016.481.485.

Rezaei, F., Richard, T.L., Logan, B.E., 2009. Analysis of chitin particle size on maximum power generation, power longevity, and Coulombic efficiency in solid-substrate microbial fuel cells. J. Power Sources 192, 304–309. doi 10.1016/j.jpowsour.2009.03.023.

Rikame, S.S., Mungray, A.A., Mungray, A.K., 2012. Electricity generation from acidogenic food waste leachate using dual chamber mediator less microbial fuel cell. Int. Biodeterior. Biodegrad. 75, 131–137. doi 10.1016/j.ibiod.2012.09.006.

Rozendal, R., Jeremiasse, A.W., Hamelers, H.V.M., Buisman, C.J.N., 2008. Hydrogen production with a microbial biocathode. Environ. Sci. Technol. 42, 629–634. doi 10.1021/es071720+.

Rozendal, R.A., Leone, E., Keller, J., Rabaey, K., 2009. Efficient hydrogen peroxide generation from organic matter in a bioelectrochemical system. Electrochem. Commun. 11, 1752–1755. doi 10.1016/j.elecom.2009.07.008.

Rumsey, I.C., Aneja, V.P., 2014. Measurement and modeling of hydrogen sulfide lagoon emissions from a swine concentrated animal feeding operation. Environ. Sci. Technol. 48, 1609–1617. doi 10.1021/es403716w.

Samsudeen, N., Radhakrishnan, T.K., Matheswaran, M., 2016. Effect of isolated bacterial strains from distillery wastewater on power generation in microbial fuel cell. Process Biochem. 51, 1876–1884. doi 10.1016/j.procbio.2016.06.007.

Sangeetha, T., Muthukumar, M., 2011. Catholyte performance as an influencing factor on electricity production in a dual-chambered microbial fuel cell employing food processing wastewater. Energy Sources, Part A Recover. Util. Environ. Eff. 33, 1514–1522. doi 10.1080/15567030903397966.

Sapkota, A.R., Lefferts, L.Y., McKenzie, S., Walker, P., 2007. What do we feed to food-production animals? A review of animal feed ingredients and their potential impacts on human health. Environ. Health Perspect. 115, 663–670. doi 10.1289/ehp.9760.

Scott, K., 2016. Membranes and separators for microbial fuel cells. In: Scott, K., Yu, E.H. (Eds.), Microbial Electrochemical and Fuel Cells: Fundamentals and Applications. Woodhead Publishing is an imprint of Elsevier, Cambridge, UK, pp. 153–178.

Shrestha, N., Fogg, A., Wilder, J., Franco, D., Komisar, S., Gadhamshetty, V., 2016. Electricity generation from defective tomatoes. Bioelectrochemistry 112, 67–76. doi 10.1016/j.bioelechem.2016.07.005.

Silver, M., Buck, J., Kiely, P., Guzman, J.J., 2014. Bio-electrochemical Systems. IWA Publishing, London, UK.

Simate, G.S., Cluett, J., Iyuke, S.E., Musapatika, E.T., Ndlovu, S., Walubita, L.F., Alvarez, A.E., 2011. The treatment of brewery wastewater for reuse: state of the art. Desalination 273, 235–247. doi 10.1016/j.desal.2011.02.035.

Sotres, A., Cerrillo, M., Viñas, M., Bonmatí, A., 2015. Nitrogen recovery from pig slurry in a two-chambered bioelectrochemical system. Bioresour. Technol. 194, 373–382. doi 10.1016/j.biortech.2015.07.036.

Sotres, A., Tey, L., Bonmatí, A., Viñas, M., 2016. Microbial community dynamics in continuous microbial fuel cells fed with synthetic wastewater and pig slurry. Bioelectrochemistry 111, 70–82. doi 10.1016/j.bioelechem.2016.04.007.

Stehfest, E., van den Berg, M., Woltjer, G., Msangi, S., Westhoek, H., 2013. Options to reduce the environmental effects of livestock production—comparison of two economic models. Agric. Syst. 114, 38–53. doi 10.1016/j.agsy.2012.07.002.

Sun, H.-L., 2012. Electricity generation from seafood wastewater in a single- and dual-chamber microbial fuel cell with CoTMPP oxygen-reduction electrocatalyst. J. Chem. Technol. Biotechnol. 87, 1167–1172. doi 10.1002/jctb.3741.

Sun, D., Wang, A., Cheng, S., Yates, M.D., Logan, B., 2014. *Geobacter anodireducens* sp. nov., a novel exoelectrogenic microbe in bioelectrochemical systems. Int. J. Syst. Evol. Microbiol 3485–3491. doi 10.1099/ijs.0.061598-0.

Sun, M., Zhai, L.-F., Li, W.-W., Yu, H.-Q., 2016. Harvest and utilization of chemical energy in wastes by microbial fuel cells. Chem. Soc. Rev. 45, 2847–2870. doi 10.1039/c5cs00903k.

Sundar, V., Raghava Rao, J., Muralidharan, C., 2002. Cleaner chrome tanning—emerging options. J. Clean. Prod. 10, 69–74. doi 10.1016/s0959-6526(01)00015-4.

Tanikkul, P., Pisutpaisal, N., 2015. Performance of a membrane-less air-cathode single chamber microbial fuel cell in electricity generation from distillery wastewater. Energy Procedia 79, 646–650. doi 10.1016/j.egypro.2015.11.548.

Tao, K., Quan, X., Quan, Y., 2013. Composite vegetable degradation and electricity generation in microbial fuel cell with ultrasonic pretreatment. Environ. Eng. Manag. J. 12, 1423–1427.

Tay, J.-H., Show, K.-Y., Hung, Y.-T., 2006. Seafood processing wastewater treatment. ChemInform 37, 29–66. doi 10.1002/chin.200613273.

Thassitou, P., Arvanitoyannis, I., 2001. Bioremediation: a novel approach to food waste management. Trends Food Sci. Technol. 12, 185–196. doi 10.1016/s0924-2244(01)00081-4.

Tian, Y., Mei, X., Liang, Q., Wu, D., Ren, N., Xing, D., 2017. Biological degradation of potato pulp waste and microbial community structure in microbial fuel cells. RSC Adv. 7, 8376–8380. doi 10.1039/c6ra27385h.

Ueki, A., Matsuda, K., Ohtsuki, C., 1986. Sulfate-reduction in the anaerobic digestion of animal waste. J. Gen. Appl. Microbiol. 32, 111–123. doi 10.2323/jgam.32.111.

Ueki, A., Ueki, K., Oguma, A., Ohtsuki, C., 1989. Partition of electrons between methanogenesis and sulfate reduction in the anaerobic digestion of animal waste. J. Gen. Appl. Microbiol. 35, 151–162. doi 10.2323/jgam.35.151.

Ueki, K., Ueki, A., Itoh, K., Tanaka, T., Satoh, A., 1991. Removal of sulfate and heavy metals from acid mine water by anaerobic treatment with cattle waste: effects of heavy metals on sulfate reduction. J. Environ. Sci. Health 26, 1471–1489. doi 10.1080/10934529109375708.

Velasquez-Orta, S.B., Head, I.M., Curtis, T.P., Scott, K., 2011. Factors affecting current production in microbial fuel cells using different industrial wastewaters. Bioresour. Technol. 102, 5105–5112. doi 10.1016/j.biortech.2011.01.059.

Vijay, A., Vaishnava, M., Chhabra, M., 2016. Microbial fuel cell assisted nitrate nitrogen removal using cow manure and soil. Environ. Sci. Pollut. Res. 23, 7744–7756. doi 10.1007/s11356-015-5934-0.

Vilajeliu-Pons, A., Puig, S., Pous, N., Salcedo-Dávila, I., Bañeras, L., Balaguer, M.D., Colprim, J., 2015. Microbiome characterization of MFCs used for the treatment of swine manure. J. Hazard. Mater. 288, 60–68. doi 10.1016/j.jhazmat.2015.02.014.

Vogl, A., Bischof, F., Wichern, M., 2016. Single chamber microbial fuel cells for high strength wastewater and blackwater treatment—a comparison of idealized wastewater, synthetic human blackwater, and diluted pig manure. Biochem. Eng. J. 115, 64–71. doi 10.1016/j.bej.2016.08.007.

Wagner, R.C., Regan, J.M., Oh, S.-E., Zuo, Y., Logan, B.E., 2009. Hydrogen and methane production from swine wastewater using microbial electrolysis cells. Water Res. 43, 1480–1488. doi 10.1016/j.watres.2008.12.037.

Wang, X., Feng, Y.J., Lee, H., 2008. Electricity production from beer brewery wastewater using single chamber microbial fuel cell. Water Sci. Technol. 57, 1117–1121. doi 10.2166/wst.2008.064.

Wang, X., Feng, Y., Wang, H., Qu, Y., Yu, Y., Ren, N., Li, N., Wang, E., Lee, H., Logan, B.E., 2009. Bioaugmentation for electricity generation from corn stover biomass using microbial fuel cells. Environ. Sci. Technol. 43, 6088–6093. doi 10.1021/es900391b.

Wang, Y., Guo, W.-Q., Xing, D.-F., Chang, J.-S., Ren, N.-Q., 2014. Hydrogen production using biocathode single-chamber microbial electrolysis cells fed by molasses wastewater at low temperature. Int. J. Hydrog. Energy 39, 19369–19375. doi 10.1016/j.ijhydene.2014.07.071.

Wang, J., Zheng, T., Wang, Q., Xu, B., Wang, L., 2015. A bibliometric review of research trends on bioelectrochemical systems. Curr. Sci. 109, 2204–2211. doi 10.18520/v109/i12/2204-2211.

Wang, H., Qu, Y., Li, D., Ambuchi, J.J., He, W., Zhou, X., Liu, J., Feng, Y., 2016. Cascade degradation of organic matters in brewery wastewater using a continuous stirred microbial electrochemical reactor and analysis of microbial communities. Sci. Rep. 6. doi 10.1038/srep27023.

Wen, Q., Wu, Y., Cao, D., Zhao, L., Sun, Q., 2009. Electricity generation and modeling of microbial fuel cell from continuous beer brewery wastewater. Bioresour. Technol. 100, 4171–4175. doi 10.1016/j.biortech.2009.02.058.

Wen, Q., Wu, Y., Zhao, L., Sun, Q., 2010. Production of electricity from the treatment of continuous brewery wastewater using a microbial fuel cell. Fuel 89, 1381–1385. doi 10.1016/j.fuel.2009.11.004.

Xu, N., Zhou, S., Yuan, Y., Qin, H., Zheng, Y., Shu, C., 2011. Coupling of anodic biooxidation and cathodic bioelectro-Fenton for enhanced swine wastewater treatment. Bioresour. Technol. 102, 7777–7783. doi 10.1016/j.biortech.2011.06.030.

Xu, Y., Jiang, Y., Chen, Y., Zhu, S., Shen, S., 2014. Hydrogen production and wastewater treatment in a microbial electrolysis cell with a biocathode. Water Environ. Res. 86, 649–653. doi 10.2175/106143014x13975035525500.

Yacob, S., Hung, Y., Shirai, Y., Ali Hassan, M., 2005. Treatment of palm oil wastewaters. In: Wang, L.K., Hung, Y.-T., Lo, H.H., Yapijakis, C. (Eds.), Waste Treatment in the Food Processing Industry. CRC Press, Boca Raton, FL, pp. 101–117.

You, S.-J., Zhang, J.-N., Yuan, Y.-X., Ren, N.-Q., Wang, X.-H., 2010. Development of microbial fuel cell with anoxic/oxic design for treatment of saline seafood wastewater and biological electricity generation. J. Chem. Technol. Biotechnol. 85, 1077–1083. doi 10.1002/jctb.2400.

Yu, J., Park, Y., Kim, B., Lee, T., 2015. Power densities and microbial communities of brewery wastewater-fed microbial fuel cells according to the initial substrates. Bioprocess Biosyst. Eng. 38, 85–92. doi 10.1007/s00449-014-1246-x.

Yu, N., Xing, D., Li, W., Yang, Y., Li, Z., Li, Y., Ren, N., 2017. Electricity and methane production from soybean edible oil refinery wastewater using microbial electrochemical systems. Int. J. Hydrog. Energy 42, 96–102. doi 10.1016/j.ijhydene.2016.11.116.

Zhang, X., Zhu, F., Chen, L., Zhao, Q., Tao, G., 2013. Removal of ammonia nitrogen from wastewater using an aerobic cathode microbial fuel cell. Bioresour. Technol. 146, 161–168. doi 10.1016/j.biortech.2013.07.024.

Zhang, G., Zhao, Q., Jiao, Y., Lee, D.J., 2015. Long-term operation of manure-microbial fuel cell. Bioresour. Technol. 180, 365–369. doi 10.1016/j.biortech.2015.01.002.

Zhao, F., Rahunen, N., Varcoe, J.R., Roberts, A.J., Avignone-Rossa, C., Thumser, A.E., Slade, R.C.T., 2009. Factors affecting the performance of microbial fuel cells for sulfur pollutants removal. Biosens. Bioelectron. 24, 1931–1936. doi 10.1016/j.bios.2008.09.030.

Zheng, X., Nirmalakhandan, N., 2010. Cattle wastes as substrates for bioelectricity production via microbial fuel cells. Biotechnol. Lett. 32, 1809–1814. doi 10.1007/s10529-010-0360-3.

Zhuang, L., Yuan, Y., Wang, Y., Zhou, S., 2012. Long-term evaluation of a 10-liter serpentine-type microbial fuel cell stack treating brewery wastewater. Bioresour. Technol. 123, 406–412. doi 10.1016/j.biortech.2012.07.038.

Ziara, R.M.M., Li, S., Dvorak, B.I., Subbiah, J., 2016. Water and energy use of antimicrobial interventions in a mid-size beef packing plant. Appl. Eng. Agric. 32, 873–879. doi 10.13031/aea.32.11615.

Table 1. Summary of Literature Studies Reporting Use of MFCs for Treating Brewery and Winery Wastewater

Wastewater Type	Cell Type[a]	Working Vol. (mL)	Anode Material	Cathode Material	Operation Mode	COD_{in} (mg/L)	ΔCOD (%)	Power Density mW/m^2 (mW/m^3)	Current Density mA/m^2 (mA/m^3)	CE (%)	Ref.
Alcohol	TC-MFC	84	Carbon cloth	Carbon paper-Pt		300		(627)	(3833)	< 8	(Mohamed et al., 2016)
Alcohol	TC-MFC	84	Carbon cloth	Carbon paper-Pt		300		(164)	(833)	< 1	(Mohamed et al., 2016)
Brewery	SC-MFC		Carbon cloth	Carbon cloth-Pt	Batch	84–2250	54–98	29–205		27–10	(Feng et al., 2008)
Brewery	SC-MFC		Carbon cloth	Carbon cloth-Pt		2239	85–87	435–483 (11 – 12)		21–38	(Wang et al., 2008)
Brewery	SC-MFC	4000	Carbon fiber brushes	Activated carbon	Continuous	3707 ± 220	75.4 ± 5.7	304 ± 31		1.5	(Wang et al., 2016)
Brewery	SC-MFC				Batch	3574	93	(<300)	(1100)		(Angosto et al., 2015)
Brewery	TC-MFC	200	Graphite felt with	Graphite cloth-Pt	Batch	2000	80	305	745		(Miran et al., 2015)
Brewery	SC-MFC	225	Graphite felt	Carbon cloth-Pt	Batch	510		251–552		31–41	(Yu et al., 2015)
Brewery	TC-MFC		Carbon paper	Carbon paper				1.68–38.34			(Mshoperi et al., 2014)
Brewery	3C-MFC	1200	Graphite plates	Graphite plates		850–4000	80–93	173.1	370		(Zhang et al., 2013)
Brewery	TC-MFC		Graphite felt	Graphite felt-Pt	Continuous	BOD: 125–1000	65		0.78		(Pisutpaisal and Sirisukpoca, 2012)
Brewery	SC-MFC	45	Carbon cloth anode	Carbon paper coated-Pt-PFTE	Batch	661	85		10 ± 1		(Velasquez-Orta et al., 2011)
Brewery	SC-MFC	100	Carbon fibers	Stainless steel-Activated carbon-PFTE	Continuous	1501	20.7	669 (24.1)		2.58	(Wen et al., 2010)

Wastewater Type	Cell Type[a]	Working Vol. (mL)	Anode Material	Cathode Material	Operation Mode	COD_{in} (mg/L)	ΔCOD (%)	Power Density mW/m^2 (mW/m^3)	Current Density mA/m^2 (mA/m^3)	CE (%)	Ref.
Brewery	SC-MFC	100	Carbon fiber and graphite rods	Stainless steel-activated carbon-PFTE-Pt	Continuous	626.58	40.5–43	264 (9520)	1.79	19.75	(Wen et al., 2009)
Brewery; digester influent, effluent	TC-MFC	250	Copper mesh-Ti	Copper mesh-Ti	Continuous	2250 ± 80, 480 ± 20	<82	10.69–80.01, 12.36–18.43			(Çetinkaya et al., 2015)
Wine lees	TC-MFC	500	Graphite felt	Platinum mesh		10,843 ± 3904		0.8	6.6		(Cercado-Quezada et al., 2010a)
Winery	Tubular-MFC	170	Carbon felts	Carbon felts	Semicontinuous	6850	10	58–890		3.4–42.2	(Penteado et al., 2016a)
Winery	TC-MFC	70	Carbon felt	Carbon felt	Batch	6850	< 17	105–465		2–15	(Penteado et al., 2016b)
Brewery; mixed with pig liquid manure	SC-MFC	100	Graphite granule and graphite rod	Carbon cloth-Pt	Batch	5028	53	(340)	(1200)	11	(Angosto et al., 2015)

a. TC-MFC stands for two-chamber microbial fuel cell, SC-MFC stands for single-chamber microbial fuel cell and 3C-MFC stands for three-chamber microbial fuel cell.

Table 2. Summary of Literature Studies Reporting Use of MFCs for Treating Cafeteria and Canteen Wastes

Wastewater Type	Cell Type[a]	Working Vol. (mL)	Anode Material	Cathode Material	Operation Mode	COD_{in} (mg/L)	ΔCOD (%)	Power Density mW/m^2 (mW/m^3)	Current Density mA/m^2 (mA/m^3)	CE (%)	Ref.
Cafeteria waste; fermented	TC-MFC		Carbon felt	Carbon paper-Pt	Batch			15.3			(Choi et al., 2011)
Canteen	TC-MFC		Graphite felt	Graphite felt-Pt	Continuous	BOD; 125–1000	75		0.7		(Pisutpaisal and Sirisukpoca, 2012)
Canteen	TC-MFC	1500	Graphite plates	Graphite plates	Batch	7760	74.2–98.9	16.3–123.8	27.1–54.3		(Sangeetha and Muthukumar, 2011)
Canteen waste	TC-MFC	300	Graphite	Copper sheet		103.8–513.9	44	(19,151)			(Hou et al., 2016)
Canteen waste	SC SBES	300	Graphite	Graphite air-cathode	Batch	380	72	162.4	< 4.5 mA		(Chandrasekhar et al., 2015)
Canteen waste	SC-MFC	22	Graphite fiber brush	Carbon cloth-Pt	Batch	2000–4900	77.2–86.4	371–556 (12–18)		23.5–27	(Jia et al., 2013)
Canteen waste	SC-MFC	430	Graphite plates	Graphite plates	Batch	sCOD 12,000	46.28–64.83	39.38–107.89	211–390		(Goud et al., 2011)
Canteen waste	Solid phase[b]	500	Graphite plates	Graphite plates			73–76	41.8–170.81			(Mohan and Chandrasekhar, 2011)
Cafeteria waste leachate	SC-MFC	24	Graphite brush	Carbon cloth-Pt	Batch	58,500 ± 3000	85.1	1540		88.8	(Choi and Ahn, 2015)
Canteen waste; Diluted	SC-MFC	120	Carbon cloth	Carbon cloth-Pt-PFTE	Batch	2700 ± 20	80.8	(5.6)	(15.3)		(Li et al., 2016)

a. TC-MFC stands for two-chamber microbial fuel cell, SC-MFC stands for single-chamber microbial fuel cell and 3C-MFC stands for three-chamber microbial fuel cell.
b. This terminology was used because the waste was in solid phase. The design of the cell was conceptually similar to a single-chamber MFC.

Table 3. Summary of Literature Studies Reporting Use of MFCs for Treating Dairy Wastewater

Wastewater Type	Cell type[a]	Working Vol. (mL)	Anode Material	Cathode Material	Operation Mode	COD_{in} (mg/L)	ΔCOD (%)	Power Density mW/m^2 (mW/m^3)	Current Density mA/m^2 (mA/m^3)	CE (%)	Ref.
Cheese whey	SC-MFC	28	Graphite fiber brush	Graphite fiber cloth-PTFE-Pt	Batch			(22.3)	10	49 ± 8	(Rago et al., 2017)
Cheese whey	TC-MFC	800	Graphite	Graphite	Batch			324.8 μW	1.19 mA		(Nasirahmadi and Safekordi, 2011)
Dairy	TC-MFC	84	Carbon cloth	Carbon paper-Pt		175.8		(503)	(1946)	< 4	(Mohamed et al., 2016)
Dairy	TC-MFC	84	Carbon cloth	Carbon paper-Pt		175.8		(38)	(404)	< 1	(Mohamed et al., 2016)
Dairy	TC-MFC	2000	Graphite plate	Graphite plate		3620	90.46	621.13	3.74 mA	37.16	(Mansoorian et al., 2016)
Dairy	TC-MFC		Carbon felt	Carbon-PFTE	Batch	2804	83.1	< 450		32.4	(Pant et al., 2016)
Dairy	TC-MFC		Graphite felt	Platinum mesh		13,650 ± 3790			1009–1796		(Cercado et al., 2014)
Dairy	TC-MFC	30	Graphite plates	Graphite plates	Batch		<91	122–197 (2.7–3.2)		8–17	(Elakkiya and Matheswaran, 2013)
Dairy	SC-MFC	45	Carbon cloth anode	Carbon paper coated-Pt-PFTE	Batch	443–700	82		25 ± 1		(Velasquez-Orta et al., 2011)
Dairy	SC-MFC	480	Graphite plate	Graphite plate	Batch	45–444	67.79–95.49	0.366–1.28 (650–1100)		4.3–14.2	(Mohan et al., 2010b)
Dairy manure	3C-MFC	617	Graphite fiber brush	Graphite fiber brush and graphite granules			4434–8302 mg/L	(< 300–14,000)		9.87–18.65	(Zhang et al., 2015)
Dairy manure	SC-MFC	28	Graphite fiber brushes	Carbon cloth-Pt-PFTE	Batch	4300	70	189		12	(Kiely et al., 2011a)
Dairy wastewater; Synthetic	TC-MFC	480	Carbon Toray	Carbon Toray	Continuous	1513–3299	39–63	92.2 (1900)	665	2.2–24.2	(Faria et al., 2017)

Wastewater Type	Cell type[a]	Working Vol. (mL)	Anode Material	Cathode Material	Operation Mode	COD_{in} (mg/L)	ΔCOD (%)	Power Density mW/m^2 (mW/m^3)	Current Density mA/m^2 (mA/m^3)	CE (%)	Ref.
Diary waste; activated sludge	TC-MFC	600	Graphite sheet	Graphite sheet	Batch			(0.5–0.715)			(Jayashree et al., 2014)
Yogurt waste	TC-MFC	500	Platinum mesh	Platinum mesh		91–594	87–91	38	<1450		(Cercado-Quezada et al., 2010b)
Yogurt waste	TC-MFC	500	Graphite felt	Platinum mesh		8169 ± 2568		2–53.8	14.5–231		(Cercado-Quezada et al., 2010a)

a. TC-MFC stands for two-chamber microbial fuel cell, SC-MFC stands for single-chamber microbial fuel cell and 3C-MFC stands for three-chamber microbial fuel cell.

Table 4. Summary of Literature Studies Reporting Use of MFCs for Treating Fruits, Vegetables, and Food Waste and Wastewater

Wastewater Type	Cell Type[a]	Working Vol. (mL)	Anode Material	Cathode Material	Operation Mode	COD_{in} (mg/L)	ΔCOD (%)	Power Density mW/m^2 (mW/m^3)	Current Density mA/m^2 (mA/m^3)	CE (%)	Ref.
Baker's yeast	TC-MFC	100	Carbon felts	Carbon felts	Batch	3500–15,000	< 40	9.75–18.41			(Liakos et al., 2017)
Bakery	SC-MFC	45	Carbon cloth	Carbon paper coated-Pt-PFTE	Batch	651	86		10 ± 1		(Velasquez-Orta et al., 2011)
Chilled ready-meal food production	Tubular-MFC	1000	Carbon veil	Carbon cloth	Continuous	843–1161	67–84	3.34–5.86			(Boghani et al., 2017)
Composite vegetable waste	SC-MFC	430	Graphite plates	Graphite plates	Batch	52,000	51.08–62.86	57.38–215.71			(Mohan et al., 2010a)
Fermented apple juice	TC-MFC	500	Graphite felt	Platinum mesh		3501 ± 2510		10.2–78	56.8–209		(Cercado-Quezada et al., 2010a)
Food	TC-MFC	84	Carbon cloth	Carbon paper-Pt	Batch	754		(1007)	(5524)	12	(Mohamed et al., 2016)
Food	TC-MFC	84	Carbon cloth	Carbon paper-Pt	Batch	754		(190.5)	(853)	7.6	(Mohamed et al., 2016)
Food industry	SC-MFC	250	Carbon cloth	Carbon cloth	Batch	810	64.2		0.78 mA		(Rasep et al., 2016)
Food industry	TC-MFC	250	Carbon cloth	Carbon cloth	Batch	810	62.96		0.72 mA		(Rasep et al., 2016)
Food processing	SC-MFC	250	Carbon paper	Carbon-Pt		sCOD; 595	95	371 ± 10			(Oh and Logan, 2005)
Food processing	TC-MFC	250	Carbon paper	Carbon-Pt		sCOD; 595	95	81 ± 7			(Oh and Logan, 2005)
Food waste leachate	TC-MFC	75.6	Carbon felt	Carbon felt	Batch	1000	74.1–85.4	(425.3–5591)		12.1–13.5	(Li et al., 2013)
Food waste leachate	TC-MFC	1200	Carbon electrode	Carbon electrode	Batch	5000	90	(15140)	(66750)		(Rikame et al., 2012)
Soy-based food	TC-MFC		Carbon felt	Carbon-PFTE	Batch	3107	71.4	< 100		18.5	(Pant et al., 2016)

Wastewater Type	Cell Type[a]	Working Vol. (mL)	Anode Material	Cathode Material	Operation Mode	COD_{in} (mg/L)	ΔCOD (%)	Power Density mW/m^2 (mW/m^3)	Current Density mA/m^2 (mA/m^3)	CE (%)	Ref.
Tomato seeds and skin	TC-MFC		Graphite felt	Graphite felt	Batch	3000		132	456		(Shrestha et al., 2016)
Tomatoes Cull	TC-MFC		Graphite felt	Graphite felt	Batch	2000		256	1504		(Shrestha et al., 2016)
Vegetable waste	TC-MFC	35	Granular graphite and Graphite rod	Carbon Paper	Batch	sCOD; 1000–1500	87	(596–1019)		7.1–32.6	(Tao et al., 2013)
Potato	SC-MFC	28	Graphite fiber brushes	Carbon cloth-Pt-PFTE	Batch	7700	89	217		21	(Kiely et al., 2011a)
Potato processing	3C-MFC	800	Graphite particles	Graphite felt and graphite rods		1000	80		250–400 μA		(Durruty et al., 2012)
Potato pulp waste	SC-MFC	25	Graphite brush	Carbon Cloth	Batch	2000–25,000	55.4–68.4	(20,400–32,100)		18–56	(Tian et al., 2017)
Potato waste	TC-MFC	240	Carbon felts	Carbon felts	Batch	1569–4245	39.5–89.6	1.4–6.8	5–150	0.3–43.6	(Du and Li, 2016)

a. TC-MFC stands for two-chamber microbial fuel cell, SC-MFC stands for single-chamber microbial fuel cell and 3C-MFC stands for three-chamber microbial fuel cell.

Table 5. Summary of Literature Studies Reporting Use of MFCs for Treating Animal Processing and Meat Industry Waste and Wastewater

Wastewater Type	Cell type[a]	Working Vol. (mL)	Anode Material	Cathode Material	Operation Mode	COD_{in} (mg/L)	ΔCOD (%)	Power Density mW/m^2 (mW/m^3)	Current Density mA/m^2 (mA/m^3)	CE (%)	Ref.
Cow manure, fruit waste and soil	TC-MFC	143	Graphite rod	Graphite rod			< 71	31.92 ± 4	190 ± 9.1		(Vijay et al., 2016)
Cow's urine	TC-MFC	400	Carbon felt	Carbon felt	Batch	150–3000	45–82	(0.64–5.23)	(3.87–14.42)		(Jadhav et al., 2016)
Goat rumen fluid	TC-MFC	2500	Copper	Zinc				9700	0.24 A		(Meignanalakshmi and Kumar, 2016)
Goat rumen fluid and hay	4 TC-MFC in series	2500	Copper	Zinc				34,390–42,110	0.74–0.82 A		(Meignanalakshmi and Kumar, 2016)
Manure wash	TC-MFC	1850	Graphite fiber brush	Carbon cloth-Pt	Batch			216 (2000)	1380	1.3–5.2	(Zheng and Nirmalakhandan, 2010)
Manure; Diluted	TC-MFC	1850	Graphite fiber brush	Carbon cloth-Pt	Batch			46–93 (400–800)	370–780	1.3–5.2	(Zheng and Nirmalakhandan, 2010)
Meat packing	SC-MFC	28	Carbon paper	Carbon paper	Batch	6010	> 86; diluted	139	1150	2.3–6.0	(Heilmann and Logan, 2006)
Slaughter house	TC-MFC	1000	Graphite	Zinc, graphite, and copper	Batch	10,815	67.9	700	318		(Christwardana et al., 2016)
Slaughter house	Tubular-MFC				Continuous	1000	99	165	472		(Ismail and Mohammed, 2016)
Swine	TC-MFC	1000	Carbon	Carbon rod		5400	85.92	3.55–88.45	0.14–0.49 mA		(Egbadon et al., 2016)
Swine	2 SC-MFC	100	Graphite fiber brushes	Activated carbon-PVDF-carbon black	Continuous	7000–7500	59 ± 6	700–750 (2800–3000)	1400–1600		(Kim et al., 2016)
Protein food industry	TC-MFC	1500	Graphite sheets	Graphite sheets	Continuous	1900	86	230.3	527	5–21	(Mansoorian et al., 2013)
Swine	SC-MFC	70	Carbon felt	Carbon paper-Pt	Batch	60,000	76–91	1000–2300	6000–7000	37–47	(Ichihashi and Hirooka, 2012)

Wastewater Type	Cell type[a]	Working Vol. (mL)	Anode Material	Cathode Material	Operation Mode	COD_{in} (mg/L)	ΔCOD (%)	Power Density mW/m^2 (mW/m^3)	Current Density mA/m^2 (mA/m^3)	CE (%)	Ref.
Swine	TC-MFC	450 + 350	Graphite granule and graphite rod	Carbon felt-Fe_2O_3	Batch	1652	62.2–76.7	(3.1–7.9)	1.7–2.8 mA		(Xu et al., 2011)
Swine	SC-MFC		Graphite brush		Batch		8–75				(Wagner et al., 2009)
Swine	TC-MFC SC-MFC	250	Carbon paper	Carbon-Pt	Batch	8320 ± 190	88–92	261	1400	8	(Min et al., 2005)
Swine farm	TC-MFC		Carbon fiber brush	Carbon cloth-Pt	atch			880–1056			(Ma et al., 2016)
Swine farm	SC-MFC	128	Carbon fiber-Fe^{2+}	Carbon fiber-stainless steel mesh	Batch	6825 ± 571	63.5–71.9	20–256	88–4000	0.9–39	(Estrada-Arriaga1 et al., 2015)
Swine manure	TC-MFC	420	Granular graphite and graphite rod	Granular graphite and graphite rod	Continuous	2200 ± 665	2.02–2.09 $kg/m^3/d$	2–20		5–24	(Vilajeliu-Pons et al., 2015)
Swine manure	SC-MFC	28	Carbon paper	Carbon-Pt	Batch	8270 ± 120	84	228			(Kim et al., 2008)
Swine manure; Diluted	SC-MFC	65	Carbon felt	Commercial Gas Diffusion Cathode-PFTE	Batch	2243 ± 25	15	28 ± 20		24 ± 3	(Vogl et al., 2016)
Swine slurry	TC-MFC	504	Carbon felt	Stainless steel mesh	Batch	6512	17–21		250		(Cerrillo et al., 2016)
Swine slurry	TC-MFC	269	Granular graphite and carbon felt	Stainless steel mesh in	Continuous	6908 mg/kg		(763–5623)			(Sotres et al., 2016)
Swine slurry liquid	TC-MFC	336	Carbon felt mesh	Stainless steel mesh	Continuous	3462	13.1–50.9	9.4–46.1	66.4–146.8	0.7–6.9	(Sotres et al., 2015)
Swine slurry; Digested	TC-MFC	504	Carbon felt	Stainless steel mesh	Batch	7951	7–12		225		(Cerrillo et al., 2016)

a. TC-MFC stands for two-chamber microbial fuel cell and SC-MFC stands for single-chamber microbial fuel.

Table 6. Summary of Literature Studies Reporting Use of MFCs for Treating Sugar-Based and Distillery Wastewater

Wastewater Type	Cell type[a]	Working Vol. (mL)	Anode Material	Cathode Material	Operation Mode	COD_{in} (mg/L)	ΔCOD (%)	Power Density mW/m^2 (mW/m^3)	Current Density mA/m^2 (mA/m^3)	CE (%)	Ref.
Chitin solution	SC-MFC	300	Carbon brush	Carbon cloth-Pt	Batch			76–272		18–56	(Rezaei et al., 2009)
Chitin wastewater; fermented	TC-MFC	100	Carbon felt	Carbon felt	Batch				8.77 μA/cm^2		(Li et al., 2017)
Corn Stover Powder and solids	SC-MFC		Carbon paper	Carbon cloth-Pt	Batch			331–343			(Wang et al., 2009)
Distillery	TC-MFC	210	Graphite plate	Graphite plate	Batch	3200–6400	46.2–64.8	70–123.5	265–323.4	13.2–27	(Samsudeen et al., 2016)
Distillery	SC-MFC	28	Carbon cloth	Carbon cloth-Pt	Batch	125–3000	29.5–56.7	(5.46)	6.6–77.7		(Tanikkul and Pisutpaisal, 2015)
Distillery waste—Digested	TC-MFC	200	Graphite rods	Graphite rods	Batch		TOC; 60.78 ± 0.95	(31490)			(Deval et al., 2017)
Molasses	SC-MFC	900	Carbon felt	Air diffusion electrode	Continuous	10,000	90.2 ± 1.63	7.9 ± 2.56	57.3 ± 9.91		(Lee et al., 2016)
Molasses	SC-MFC	900	Carbon felt	MEET	Continuous	10,000	88.7 ± 3.34	7.5 ± 0.67	56.7 ± 2.52		(Lee et al., 2016)
Molasses	TC-MFC	900	Carbon felt	Carbon felt	Continuous	10,000	50.3 ± 5.06	17.0 ± 10.15	80.2 ± 29.11		(Lee et al., 2016)
Molasses	TC-MFC	300	Carbon cloth	Carbon cloth-Pt	Batch	130,000	67	2425	2600		(Ali et al., 2016)
Sugar mill	TC-MFC	500	Carbon felt	Carbon felt	Batch	7210	56	140	50	70	(Kumar et al., 2015)

a. TC-MFC stands for two-chamber microbial fuel cell and SC-MFC stands for single-chamber microbial fuel cell.

Table 7. Summary of Literature Studies Reporting Use of MFCs for Treating Seafood Wastewater

Wastewater Type	Cell Type[a]	Working Vol. (mL)	Anode Material	Cathode Material	Operation Mode	COD_{in} (mg/L)	ΔCOD (%)	Power Density mW/m^2 (mW/m^3)	Current Density mA/m^2 (mA/m^3)	CE (%)	Ref.
Seafood	Tubular-MFC	50	Activated carbon fiber felt	Activated carbon fiber felt	Continuous	700 ± 50	83	105–222 (221–886)		<30	(Jayashree et al., 2016)
Seafood	SC-MFC	26	Carbon cloth-steel mesh	Carbon cloth-Pt-PTFE	Batch	1015.6	85.1	343.6–358.8	360–1270	0.38–14.2	(Sun, 2012)
Seafood	TC-MFC	26	Carbon cloth-steel mesh	Carbon cloth-Pt-PTFE	Batch	1015.6	64.7	258.7–291.6	360–1270	0.65–20.3	(Sun, 2012)
Seafood	TC-MFC	98	Granular graphite and Graphite rod	Granular graphite and Graphite rod	Continuous	2102–2522	28.2–80.2	(8900–16,200)	(31,100–41,700)	2.11–15.2	(You et al., 2010)

a. TC-MFC stands for two-chamber microbial fuel cell and SC-MFC stands for single-chamber microbial fuel.

Table 8. Summary of Literature Studies Reporting Use of MFCs for Treating Oil Wastewater

Wastewater Type	Cell Type[a]	Working Vol. (mL)	Anode Material	Cathode Material	Operation Mode	COD_{in} (mg/L)	ΔCOD (%)	Power Density mW/m^2 (mW/m^3)	Current Density mA/m^2 (mA/m^3)	CE (%)	Ref.
Palm oil mill	TC-MFC	450	PACF carbon felt	PACF carbon felt		1000	70	22	~ 180	24	(Baranitharan et al., 2015)
Soybean oil	SC-MFC	18	Graphite felt	Carbon cloth-PTFE-Pt		40,000	77.9	2240 (31,600)	658	20.1	(Hamamoto et al., 2016)
Soybean oil refinery	SC-MFC	2	Graphite fiber Brush	Stainless steel mesh	Batch	2900 ± 100	~ 96.4	746 (~ 24,100)		9.3–33.6	(Yu et al., 2017)
Vegetable oil	TC-MFC	500	Ti wire	Carbon cloth	Batch	925	86				(Abbasi et al., 2016)

a. TC-MFC stands for two-chamber microbial fuel cell and SC-MFC stands for single-chamber microbial fuel cell.

Table 9. Summary of Literature Studies Reporting Use of MECs for Treating Food Waste and Food Wastewater

Wastewater Type	Cell Type[a]	Working Vol. (mL)	Anode Material	Cathode Material	Operation Mode	$E_{app.}$ (V)	COD_{in} (mg/L)	ΔCOD (%)	r_{cat} (%)	r_{H2} (%)	Q (m^3 H_2/m^3/day)	CE (%)	Ref.
Beer wastewater	SC-MEC	2100	Graphite fiber brushes	Circular stainless steel mesh	Semicontinuous	0.5–0.9	1125 ± 66	65–80		32.1–91.2	0.14 (CH4)	5–32.7	(Guo et al., 2017)
Cheese whey	SC-MEC	32			Batch	0.8	2000		49 ± 2				(Rago et al., 2017)
Cheese whey; Diluted and Fermented	MEC	50	Carbon felt	Gas diffusion electrode-Ni	Continuous	1	15.26	82			0.5		(Moreno et al., 2015)
Glycerol, starch and milk	SC-MEC	28	Graphite fiber brush	Graphite fiber cloth-Pt-PFTE	Batch	0.8		74–100	91		0–0.94	13–29	(Montpart et al., 2015)
Milk	SC-MEC	28	Graphite fiber brush	Graphite fiber cloth-Pt-PFTE	Batch	0.8	1000	73.5	14		0.086	36–52	(Montpart et al., 2015)
Molasses	SC-MEC	25	Graphite-fiber brush anodes	Carbon cloth—with and without Pt	Batch	0.6–0.8	2000		54.3–102	45.5–94	2.27–10.72	91–93	(Wang et al., 2014)
Potato	SC-MEC	28	Graphite fiber brushes	Carbon cloth-Pt-PFTE	Batch	0.8	7700	79			0.74	80	(Kiely et al., 2011a)
Soybean oil refinery	SC-MEC	22	Graphite fiber brush	Stainless steel mesh	Batch	1.2	2900 ± 100	95.8			0.133 ± 0.005 CH_4		(Yu et al., 2017)
Starch	SC-MEC	28	Graphite fiber brush	Graphite fiber cloth-Pt-PFTE	Batch	0.8	1185	85.1				15–28	(Montpart et al., 2015)
Swine	3c-MEC	2000	Carbon graphite	Carbon graphite	Continuous	0–2	10,136.9 ± 850.5	59.7–67					(Lim et al., 2012)
Swine	TC-MEC				Batch	0.2–1	1298	45–52			0.061	9–30	(Jia et al., 2010)
Swine	SC-MEC				Batch		12,825	69–75	29–61	17–20	0.9–1	29–70	(Wagner et al., 2009)

Wastewater Type	Cell Type[a]	Working Vol. (mL)	Anode Material	Cathode Material	Operation Mode	$E_{app.}$ (V)	COD_{in} (mg/L)	ΔCOD (%)	r_{cat} (%)	r_{H2} (%)	Q (m^3 H_2/m^3/day)	CE (%)	Ref.
Swine slurry	TC-MEC	504	Carbon felt	Stainless steel mesh	Batch	0–0.2	6512	29–35				7–9	(Cerrillo et al., 2016)
Swine slurry liquid	TC-MEC		Carbon felt mesh	Stainless steel mesh	Continuous	0.1–0.8	3462	13.5–53.8				3.2–56.9	(Sotres et al., 2015)
Swine slurry; Digested	TC-MEC	504	Carbon felt	Stainless steel mesh	Batch	0–0.2	7951	17–25				11–18	(Cerrillo et al., 2016)
Table olive oil brine processing	MEC	336	Graphite plates	Pt-radium grid	Batch	0.2–0.8		29			109 ± 21 N mL CH_4/g COD_{rem}	30	(Marone et al., 2016)
Winery	SC-MEC				Batch	0.9	2200	47			0.17	50	(Cusick et al., 2010)

a. TC-MEC stands for two-chamber microbial electrolysis cell and SC-MEC stands for single-chamber microbial electrolysis cell.